# Advanced Space Situational Awareness through Automated Conjunction Risk Analysis System (CRAMS)


V. Abbasi*, M. Doyon**, R. Babiker***, D. Golla****

Satellite Operations, Ground Infrastructure & Applications, Space Utilization, Canadian Space Agency, Canada

* e-mail: viqar.abbasi@asc-csa.gc.ca

** e-mail: michel.doyon@asc-csa.gc.ca

*** e-mail: rahman.babiker@asc-csa.gc.ca

**** e-mail: david.golla@asc-csa.gc.ca



## Abstract

The Canadian Space Agency (CSA) has refined its operational capability to better analyze the threat to its space assets as a result of the ever-growing problem of space debris. The Conjunction Risk Assessment and Mitigation System (CRAMS) anchors CSA's new Space Debris Centre of Expertise, a segment of its satellite operations facility at the forefront of space situational awareness in Canada. CRAMS provides automated, accurate and on-time risk assessment data, almost immediately after the initial notification of a potential close approach. The automation allows CRAMS to support multiple satellite missions with little to no overhead, providing satellite operators with maximum flexibility to make the right operational decision and minimize mission impacts due to space debris threats. CRAMS reports are rapidly distributed, easy-to-use and rigorously validated, making them ideal for decision-making support in a time-sensitive context. They are also contributing to increased awareness of the space debris problem and important new partnerships.


## 1 Introduction

Space debris threats have become a routine hazard faced by all satellite operators, particularly since the 2007 Fengyun-1C disintegration and the 2009 Cosmos2251/Iridium33 collision resulted in thousands of new pieces of uncontrolled space debris in valuable Low-Earth-Orbits (LEO). Canadian satellites have not been exempt from this threat. Over several years of experience with potential conjunction events involving its operational assets, CSA has developed a multi-mission conjunction risk assessment and mitigation system (CRAMS). The purpose of this tool is to improve the efficiency with which conjunction events are handled and processed. At present, the Joint Space Operations Centre (JSpOC) has the most complete and accurate database of all space assets and their ephemeris and provides notification service to satellite operators, including CSA, to warn them of potential conjunction events to prevent any further collisions in space. JSpOC policy currently provides warning of a potential conjunction event with 72 hours of the event. This creates a restricted timeline in which to assess, plan and execute any response to the event. As a result, any efficiencies in the process are considered very valuable. The CRAMS system and associated processes will continually evolve with operational experience.

## 2 Operational History

The history of close approach events and related processes has been one of increasing information. Originally, notices from JSpOC were received infrequently with very little information about the timing of the close approach event and the relative separation of the two events. Later following the game-changing 2007 and 2009 events and renewed focus in JSpOC to ensure no more collisions in space, a more formalized agreement was entered into with JSpOC where they would agree to notify CSA in the event any object approached within a specified miss distance (Overall miss < 1000m and Radial miss < 200m). At first the information only contained 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 determine the combined in-track errors of the two objects, but with only radial errors available, simple approximations were made (in-track errors = 10*radial errors). A "serious" event was one where the in-track separation of the two objects both resided within the combined errors and a maneuver would be sized to increase the separation so that they were not both within the error margin. Later, JSpOC began supplying errors for both objects in all three coordinates. When this was available, and through the use of supplemental data sources, the geometry of the event was analyzed and a "close approach box" was constructed based on a transformation of the secondary object's errors into the primary object's frame. Maneuvers were sized to ensure that the separation of the two objects was greater than the size of the close approach box.

Eventually, JSpOC began providing "Conjunction Summary Messages" (CSMs) which contained information regarding the two objects involved, including the location and velocity of both objects in the Earth Fixed reference frame, and full covariance matrices at the time of closest approach. With this detailed set of information came the desire to more properly characterize the severity of close approach events, and introduce the probability of collision into both the evaluation of the severity of the event, and the "exit criteria" for any escape maneuvers.

As the frequency of CSMs increased, and as CSA refined its related tools and processes, automation was the natural next step. CRAMS was born to first automatically perform all the "close approach box" calculations (which were previously performed manually) and then further evolved to replace the "close approach box" method with a more refined methods based on the probability of collision. Details of the probability implementation currently in CRAMS are provided in Section 6. Probability calculations were validated with other space agencies, commercial operators and commercial tools to ensure that a consistent and credible methodology was applied.

Over the years, CRAMS adapted to various formats of the CSM, all the while serving its steadily increasing "customer" base (which now counts 18 satellites), providing detailed analysis and value-added information within minutes of the initial notification published by JSpOC. By taking responsibility for the processing of JSpOC data, CRAMS allowed operators to concentrate on the appropriate decision for the satellite in response to the event, rather than adapting tools and processes to changing data formats.

In 2014, JSpOC is replacing the CSM format with a new and revamped "Conjunction Data Message" CDM format. In keeping with its tradition, CRAMS is being updated to adapt to the new format, allowing a seamless transition for all the various satellites subscribed to CRAMS conjunction analysis reports.

## 3 Operational Context and Processes

CRAMS is a major component of the CSA's Space Debris Centre of Expertise. The CRAMS functionality was originally developed to automate close approach data analysis processes for CSA's fleet of satellites. These processes were similar across different missions, and the risk assessment calculations were time-consuming when done manually. The lightweight and generic system design of CRAMS allowed CSA to start supporting other Canadian satellite missions, where close approach processes perhaps had not matured to the same extent as they had at CSA. The system is now supporting many commercial and government satellite missions, and also providing space situational awareness to government partners, as shown in the overall context diagram in Figure 1.

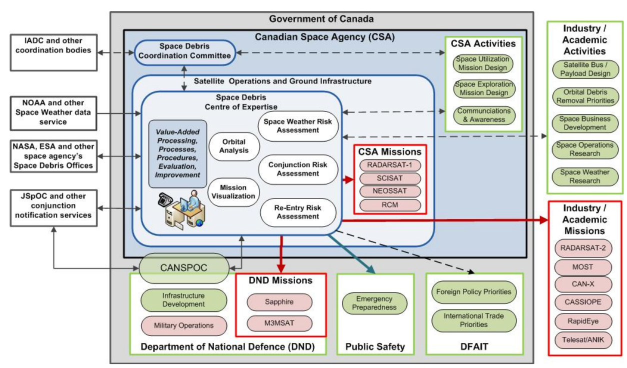


**Figure 1: Space Debris Centre of Expertise context**

Figure 2 shows the more detailed conjunction event management process using CRAMS. The link between multi-mission operations and mission-specific operations is shown in this figure.

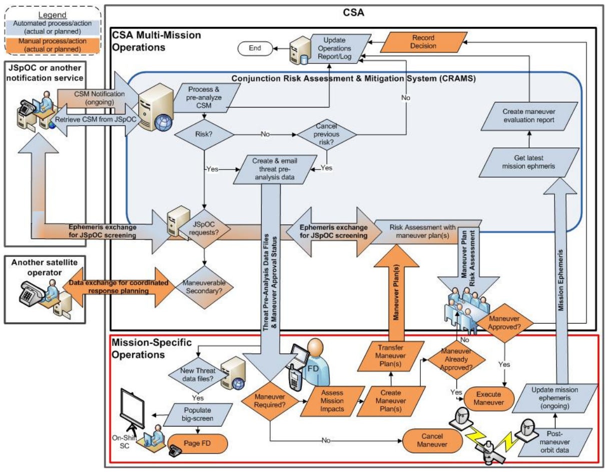


**Figure 2: CRAMS multi-mission conjunction management**

At present, the following CRAMS capabilities are operational and automated:

- Retrieval of conjunction data from JSpOC
- Processing and analysis CSM for risk assessment and generate recommendations
- Creation & emailing of threat analysis reports to mission-specific distribution list, including probability information and maneuver tradespace

Although CRAMS reports provide recommendations, CRAMS does not make manoeuvring decisions, nor does it create maneuver plans. This responsibility is left to mission-specific operations. The main CRAMS analysis software, which executes within the automated CRAMS system, may also be used manually by operations staff in order to study potential maneuver options. This is useful to evaluate a maneuver plan for risk assessment.

# 4 CRAMS Operational Products

The CRAMS system provides different products to support the organization at multiple levels.

Automated processing systems use the XML output to trigger certain operational responses in response to conjunction events. At CSA, the XML format is used by automated email transfer software to determine which email distribution list and which attachments are to be included with the email. The same file also contains information about whether an alert is needed to page the on-call flight dynamics analyst to analyze the data and potentially plan a collision avoidance maneuver.

For humans, an Excel spreadsheet is the main CRAMS product, delivered via email to the required personnel at each conjunction notification, and also archived for later reference as required. The spreadsheet has a summary sheet which can be used by management to see the notification history and evolution of the current threat over time, understand the probability of collision, and graphically visualize the conjunction geometry, including error ellipses and where and when the potential conjunction would take place. An example of the summary sheet is shown in Figure 3 below.

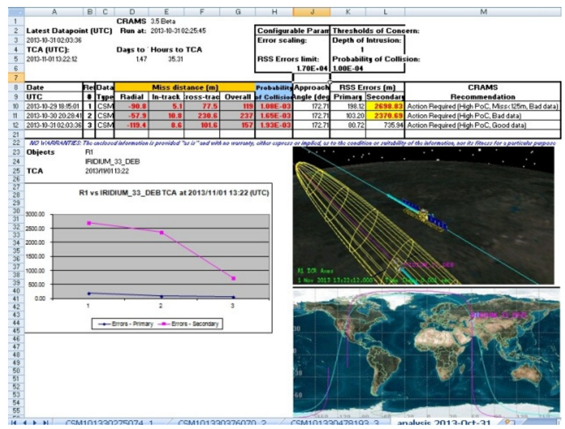

**Figure 3: CRAMS summary Excel spreadsheet**

For technical staff responsible to make a maneuver decision and for the flight dynamics analyst responsible to develop a maneuver plan, more detailed information is required. The CRAMS Excel spreadsheet provides one technical data sheet for each conjunction notification, providing all the technical information from JSpOC plus a large set of value-added content based on the automated analysis. The value-added content includes a detailed maneuver trade space, showing the impact of potential maneuver options on miss distance and probability of collision, which is used to help plan and evaluate potential spacecraft collision avoidance maneuvers. Figure 4 below shows the detailed CSM sheet featuring all JSpOC-provided content plus the value-added analysis data on the same sheet.

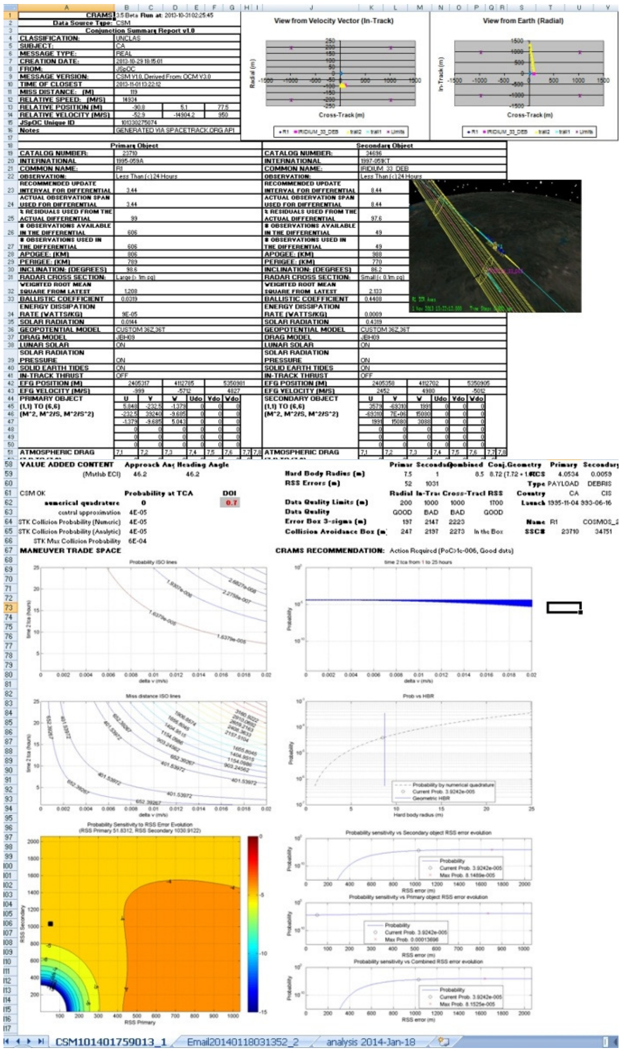


**Figure 4: CRAMS technical data and value-added content**

Of particular interest in the CRAMS detailed report are the probability sensitive plots and maneuver trade space plots. These are discussed in the next section, where the process of risk analysis using CRAMS is discussed in more detail.

# 5 Collision Risk Analysis using CRAMS

This section discusses the collision risk analysis processes using CRAMS. These processes include risk identification, assessment and reporting of results to supported missions. CRAMS recommends action in its report when the probability is above 1.0E-06, the miss distance is smaller than 200 meters, when the conjunction summary message is based on an owner ephemeris or in case of any errors when processing the data. Since each mission may have its own mission-specific maneuver decision criteria (and since the maneuver option is only available to a subset of satellites), the action recommended by CRAMS generally leads to further mission-specific analysis by the flight dynamics analyst. CSA satellites use a probability threshold of 1.0E-04 with good data quality and a miss distance keep-out zone of 125 meters regardless of the data quality. The data quality cut-off limit is one-σ error of 1.7 km in the primary or secondary object. This is derived from the accepted errors assumed in two-line-element (TLE) sets for LEO regime orbits and the decision not to use TLEs in collision risk assessment and mitigation.

The following sections show some examples of how the flight dynamics analyst would use some of the features of the CRAMS reports to further analyze the collision risk. In the example below, the close approach event was initially reported about 72 hours before the time of closest approach (TCA), resulting in the first CRAMS report, and then three data updates were provided by JSpOC, resulting in subsequent corresponding CRAMS reports.

## 5.1 Probability Sensitivity

The improving quality of data with subsequent measurements leads to smaller covariance in the position estimates of the two objects and clearly impacts the probability of collision. In order to provide analysts with a means of predicting the impact of future data points, a number of probability sensitivity plots were introduced. One of these, as shown in Figure X, shows the evolution of probability as a function of measurement errors. On the figure, the X-axis and Y-axis represent the root-sum-square of the errors of the primary object and secondary object, respectively. The current uncertainty of the both objects is represented by the black square in the probability sensitivity plot above. The secondary object is usually space debris which is tracked more closely by JSpOC when the object is involved in close approaches, resulting in improved error estimates as we approach the time of closest approach (TCA). Finally, the colors represent a kind of "heat map" with red/orange representing a higher probability of collision (1E-05 and up) and lower probabilities gradually heading towards blue and white.

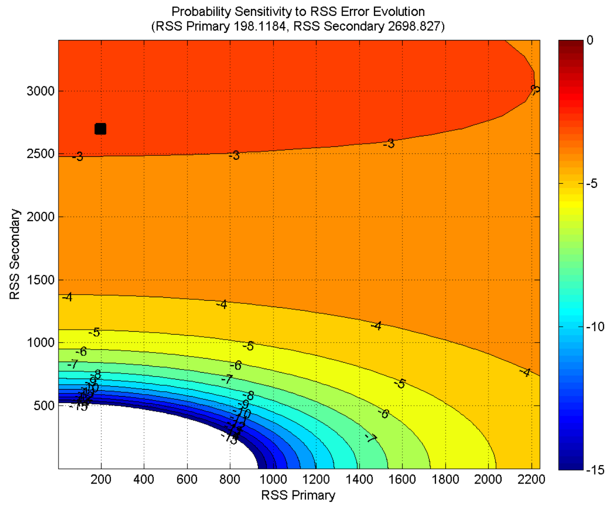


**Figure 5: Probability Sensitivity plot: data point 1**

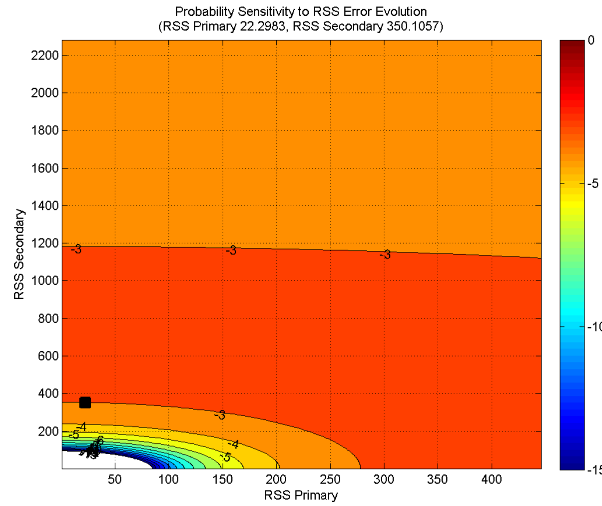


**Figure 6: Probability sensitivity plot: data point 3**

The above probability sensitivity plot (Figure 5) corresponds to the first data point (first conjunction notification) about 72 hours before TCA. In this plot, the black square indicates the current probability is 1.1E-03. This is considered above the maneuver decision criterion of 1E-04. However, there is a significant margin for data quality of the secondary object to improve which would drive the probability significantly below that threshold if the miss distance remains the same. For the same conjunction referenced above, the sensitivity plot generated following the third update, about 24 hours before TCA, of the same close approach event (Figure 6 below) shows a significant improvement in the data quality almost by a factor of eight but at the same time the miss distance decreased in such a way that the probability slightly dropped but remained more or less on the threshold at the vale of 9.73E-04. So the event required an avoidance maneuver based on the probability criterion.

In the above cases, the secondary object was a debris object and the increased data quality (reduced errors in the secondary object) is likely due to the additional tracking measurements of the secondary object once it is involved in a close approach situation. It is fairly typical for initial estimates of debris objects to have large errors (in the kilometers range), which are then reduced (to a few hundred meters) as more tracking becomes available.

In another event shown below (Figure 7), the calculated probability is also above the action threshold of 1E-04. In this case, the errors corresponding to the secondary object show that the data quality is almost the best attainable for these two objects and therefore no room for data quality improvement which make this event more critical than that of the previous case. Even if this were the first data point for the event, this probability is unlikely to get better and the best decision could be taken to maneuver sooner rather than wait for more data.

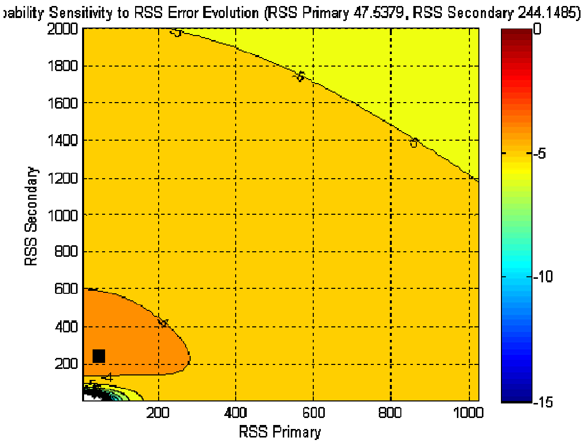


**Figure 7: Probability Sensitivity plot: another case**

By having this information (and other similar sensitivity plots) readily available in every CRAMS report, operational staff is able to quickly make a decision on whether it is better to act now in response to a close approach event (because the threat will remain high regardless of new measurements), or whether it is better to wait for new measurements (because the threat will quickly decrease when data quality improves). If a maneuver decision is made, the maneuver trade space plots will show the impact of various maneuver options. These are discussed in the next section.

## 5.2 Maneuver Trade Space for Risk Mitigation

The collision risk is mitigated by avoidance maneuvers for those spacecraft with propulsion subsystems. The maneuver trade space is a key feature that provides ISO plots of the expected miss distance and expected probability of collision for a variety of velocity change (delta-V) operations at different potential maneuver offset times from the time of close approach (TCA). The data is available in the Excel spreadsheet as tabulated values as well as easily readable plots. By showing a wide range of potential maneuver options and resulting miss distance and probability, the impact on mission may also considered when selecting a maneuver from the trade space.

Using the same conjunction event example shown previously in Figure 5 and Figure 6, a set of the trade space graphs is shown below (Figure 8 and Figure 9). From the two graphs, a 5 cm/s avoidance maneuver lowers the probability of collision to 3.16E-09 at a separation distance of 301 m when performed 9 hours before time of close approach. In practice avoidance maneuvers are performed earlier to increase the separation significantly and lower the probability below the threshold value of 1.0E-09. The required change in velocity (delta V) may change accordingly. Since there is a set of maneuver trade space plots provided with each data update, and the range of maneuver offset times is adjusted accordingly each time, the mission team always has up-to-date maneuver tradespace information. This is particularly useful for missions that perform routine orbit maintenance maneuvers, because a potential collision avoidance maneuver could be coupled with routine orbit maintenance maneuver to save fuel.

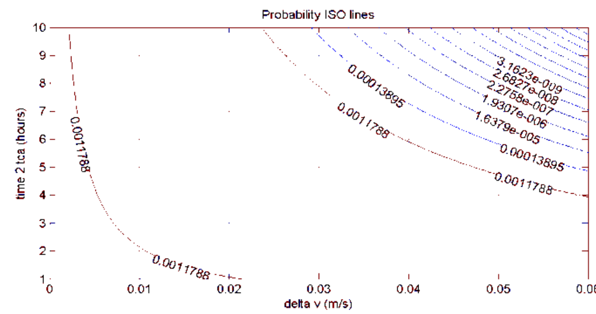


**Figure 8: Maneuver trade space: Probability ISO plot**

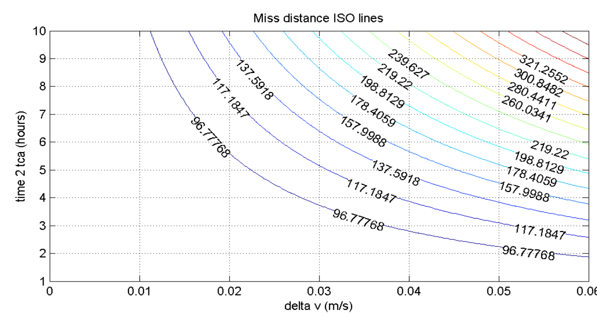


**Figure 9: Maneuver trade space: Miss distance ISO plot**

# 6 Probability of Collision implementation

This section discusses the details of the probability of collision numerical computations which are at the heart of the CRAMS system. In Matlab, CRAMS performs numerical computation of the collision probability from the data provided by and extracted from the JSpOC-provided CSM. The CSM contains the position and velocity vectors for both the primary and secondary objects expressed in the TDR (True-of-Date Rotating) reference frame as well as the corresponding position and velocity error covariance matrices. Once extracted from the CSM, these quantities are transformed to the

TOD (True-Of-Date) inertial reference frame. This is the natural inertial reference frame to use for the provided data and it is acceptably close to ECI, differing only by the small rotations accounting for the nutation and precession of the Earth.

Working now with the relative position and velocity vectors (of the secondary object with respect to the primary object, or asset), the relative position error covariance matrix at the time of conjunction is determined by simple summation of the primary and secondary position error covariance matrices (in TOD). Moreover, assuming a short duration encounter during which the relative motion can be assumed to be rectilinear in the encounter region, this combined covariance matrix is reduced from 3 dimensions to 2 and the probability value is now independent of the error in the direction of the relative velocity vector. This reduced combined error covariance matrix is the covariance of the relative position error in the encounter plane normal to the relative velocity, and it is understood to be modeled by the covariance of a zero-mean Gaussian random 2-vector. The theory of combining the error covariance matrices and applying the rapid encounter assumption is developed fully in the books by Klinkrad [1] and Chan [2].

Further simplification for the computation of the probability of collision is based on modelling the finite dimensions of both primary and secondary objects as spheres, each with its own hard body radius. Now, when working with the relative motion, the two spheres can be combined into a single sphere by summing the hard body radii. Finally, with the application of the rapid encounter assumption, this sphere reduces to a circle of radius $R_c$.

With all of the simplifications made in the theoretical development, the resulting probability integral to be evaluated is given by:

$$\boldsymbol{P} = \frac{1}{2\pi\sqrt{|C|}} \iint_{A_c} e^{-\frac{1}{2}r^T C^{-1} r} d\tilde{x} d\tilde{z} \qquad (1)$$

where $\boldsymbol{C}$ is the reduced combined 2x2 covariance matrix, $\boldsymbol{r^T} = [\tilde{x}, \tilde{z}]$, and the area of integration, $A_c$, is the circle of hard body radius, $R_c$, whose centre is offset from the origin at the location $[0, r_{miss}]$ — the miss distance, $r_{miss}$, the magnitude of the relative position vector at the time of the conjunction, is provided in the CSM.

Just as there were simplifications made in the development of the probability integral to be computed, there are simplifications to be made in its numerical computation. The first important simplification is to diagonalize the covariance matrix by the appropriate linear transformation of variables determined by the eigenvectors of $\boldsymbol{C}$, a symmetric positive definite matrix. This amounts to a rotation of the coordinates through an angle φ given by $\tan 2\varphi = 2\frac{C_{12}}{(C_{11}^2 - C_{22}^2)}$. The resulting probability integral to be evaluated becomes:

$$P = \frac{1}{2\pi\sigma_{\bar{x}}\sigma_{\bar{z}}} \iint_{A_c} e^{-\frac{1}{2}\left[\left(\frac{\bar{x}}{\sigma_{\bar{x}}}\right)^2 + \left(\frac{\bar{z}}{\sigma_{\bar{z}}}\right)^2\right]} d\bar{x} d\bar{z} \qquad (2)$$

where $\sigma_{\bar{x}}^2$ and $\sigma_{\bar{z}}^2$ are the eigenvalues of $\boldsymbol{C}$ and the origin of the offset circle, $A_c$, becomes relocated to the position $[r_{miss}\cos\varphi, r_{miss}\sin\varphi]$.

If we now let $\bar{x} = \sigma_{\bar{x}} x$ and $\bar{z} = \sigma_{\bar{z}} z$ then, by simple substitution, the collision probability becomes:

$$P = \frac{1}{2\pi} \iint_{A_e} e^{-(x^2+z^2)/2} dx dz \qquad (3)$$

and the region of integration, $A_e$, becomes the interior of an offset ellipse defined by:

$$b^2(x-h)^2 + a^2(z-k)^2 \le a^2 b^2 \qquad (4)$$

with

$$h = h_c/\sigma_{\bar{x}} = (r_{miss}\cos\varphi)/\sigma_{\bar{x}} \qquad (5)$$

$$k = k_c/\sigma_{\bar{z}} = (r_{miss}\sin\varphi)/\sigma_{\bar{z}} \qquad (6)$$

and

$$a = R_c/\sigma_{\bar{x}} \qquad (7)$$

$$b = R_c/\sigma_{\bar{z}} \qquad (8)$$

Thus we see that the evaluation of collision probability can be performed either by the numerical integration of a *bivariate* Gaussian distribution (2) over an offset *circle,* or, equivalently, by the numerical integration of a *circular* Gaussian distribution (3) over an offset *ellipse.* The latter approach is advantageous if we further transform it into polar coordinates:

$$P = \frac{1}{2\pi} \iint_{A_e} e^{-r^2/2} r dr d\theta \qquad (9)$$

with $r$ and $\theta$ implicitly defined by $x = r\cos\theta$ and $z = r\sin\theta$.

It is clear now that the integrand, when expressed in polar coordinates, can be analytically integrated over the radial dimension, which reduces the numerical evaluation of collision probability to the numerical evaluation of a line integral over the angular dimension:

$$P = \frac{1}{2\pi}\int_{\theta_1}^{\theta_2}\left(e^{-r_1^2(\theta)/2} - e^{-r_2^2(\theta)/2}\right)d\theta \qquad (10)$$

Of course, some algebra remains to determine the angular limits of integration, $\theta_1$ and $\theta_2$, and the functions of $\theta$ defining the radial limits of integration, $r_1(\theta)$ and $r_2(\theta)$, but these are determined from the *geometry* of the ellipse, (4), and are only computed once at the start of the numerical integration subroutine. The integrand of (10), which needs to be performed multiple times, remains simple with minimal computations.

Both the double integral (2) and the line integral (10) have been computed using the Matlab subroutines *dblquad* and *quadgk*, respectively. As expected, the results are identical but the latter computation runs more than 3 times faster, an important improvement given the large number of probability computations performed in the processing of each CSM. The CRAMS probability computation has been validated by comparison with external results and in particular it has yielded identical results on over 28,000 CSMs provided by CNES.

## 7 Future Directions

Presently, CRAMS is being upgraded to JSpOC's new conjunction data message (CDM) format. This will ensure continuity of service to our supported satellite fleet and minimizes the need for all clients to adapt, a clear advantage of CSA's centralized approach. In the future, CRAMS is expected to perform additional functions autonomously such as gathering and processing mission ephemeris and creating maneuver evaluation reports. Remote query functionality for customized mission-specific analysis and automated monthly reports are also planned.

## 8 Acknowledgments

Our team recognizes the important contributions of various partners in the field of satellite operations and space debris risk management. These include other space agencies and satellite operators who have supported our software validation efforts, such as Centre national d'études spatiales (CNES), EUMETSAT, the European Space Agency (ESA) and DLR. We cannot forget our industrial partners in satellite operations, SED Systems, MDA, COMDEV, ExactEarth, Telesat, MSCI and Blackbridge, all of whom have been loyal clients of the CRAMS service and have provided valuable advice and guidance throughout development and operations. Finally, none of this would be possible without the pivotal role of the United States Joint Space Operations Centre (JSpOC) who plays the leading role in disseminating high-quality information about the potential close approaches to space actors worldwide. The entire space community is highly dependent on this service, which helps to ensure that operating satellites in space remains a feasible pursuit for all of us. With promising new international partnerships in space situational awareness being pursued by our friends in Canada's Department of National Defence (DND), CSA hopes that we can all continue to operate space missions in an increasingly safe and cost-effective manner.

## 9 Conclusions

In summary, CSA continues to innovate in the area of space situational awareness and risk management. Processes are being refined and the focus on automation and efficiency allowing the organization to support additional missions with little to no additional overhead. The trending capability of the system raises awareness of the threat faced by all space operators, which will prove invaluable when the international space community is ready to discuss priorities for debris remediation/removal. Consolidating the processing for multiple missions could eventually help prioritize space debris remediation activities (such as debris removal) and high-level planning for future missions (such as orbit selection and maneuverability requirements). In the short term, it is fostering interactions with other government departments such as the Department of National Defense (DND) and Public Safety, leading to a heightened sensitivity of operational space issues and the development of a common framework for risk management. The continued delivery of mission results in a safe and cost-effective manner requires a credible strategy on mitigating the threats from space debris. CSA's new Space Debris Centre of Expertise and its Conjunction Risk Assessment and Mitigation System (CRAMS) are designed to provide just that, in collaboration with our national and international partners in space operations.

### References

[1] Klinkrad, H, Space Debris Models and Risk Analysis, Praxis Publishing Ltd, Chichester, 2006

[2] Chan, K, Spacecraft Collision Probability, Aerospace Press, El Segundo, 2008.