LAUNCH COLLISION AVOIDANCE SENSITIVITY ANALYSIS

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ABSTRACT

The objective of this work is to estimate the potential impact that Launch Collision Avoidance (COLA) analyses could have on orbital launches from the UK.

A set of orbits representative of launch trajectories from the UK is defined, together with a time-fixed TLE catalogue, retrieved the day before the selected launch date and filtered to extract the most crowded orbits to target with the launch. The launcher mission design in this work presents a coasting arc preceding the circularisation burn and the successive orbits after injection, both included in the screening. Multiple launch screening rates are used to identify the worst-case scenario through a miss distance (MD) approach, ranging from 1-minute to 1-second. The worst-case scenario is associated to the highest number of close approaches and hence highest possibility for launch windows closure. The criteria to determine a possible collision is based on a 25 km safe separation distance, in line with current best practices in this field, as in [1]. A conjunction detection analysis for up to three days after the selected launch date is executed for the chosen orbits.

The uncertainty associated with the miss distance is one of the most relevant aspects in the collision risk computation. The more measurements are processed, the more accurate the orbit is, and more reliable the analysis. For this reason, a comparison between the statistical analysis and the MD is also performed to identify how accurate MD results are when uncertainties come into play.

1 INTRODUCTION

Performing COLA analyses is crucial to mitigate the risk of collision with an orbiting object in the crowded space around the Earth. COLA analyses intend to screen for possible conjunctions and prevent launches at times that involve probability of collision (PoC) above a predetermined screening threshold. Number and severity of conjunctions between two objects in space are generally related to:

- Destination orbit
- Time of day of launch
- Day of launch
- Launcher position and velocity

This study intends to extract the most crowded orbits that can be reached from the UK soil in order to select a worst-case scenario to examine the sensitivity of the screening process. This scenario will be associated to the launch epoch that raises the highest number of possible conjunctions and possibility for launch closures.

The conjunction analysis itself consists of two phases:

- Pre-screening on miss-distance
- Determination of the probability of collision

Both phases are included in the Conjunction Risk Service, an internal Deimos tool used to perform these tasks and to support this type of operations. Indeed, it is able to check close approaches against a fixed catalogue and evaluate the collision risk using covariance data where available, or applying heuristic methods based on objects class and orbit type otherwise.

So, a miss distance analysis will be performed to understand how the screening rate affects the accuracy of the conjunction detections. This algorithm does not evaluate the probability of collision but is fast and performs an initial filtering that reduces the computational time of the second phase execution.

The results obtained through the application of the miss distance approach will be compared with the statistical analysis of the collision involving uncertainties in objects position and velocity.

2 WORST-CASE SCENARIO DEFINITION

Orbits accessibility is generally determined by the latitude of the launch site and the direction of launch, that must be chosen to guarantee safety of the downrange population. From a proposed launch site located in the Scottish Highlands the set of orbits of interest are 83°, 90° and SSO in an altitude range between 500km and 1500km, particularly suited for scientific mission, but also very congested. The launcher is designed to deliver payloads in the class of small satellites, with its mission profile presenting a coasting arc and a circularisation burn.

Before starting performing COLA analyses, a TLE catalogue has been retrieved on the 25th of February

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
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2020 from which the most crowded orbits for the selected inclinations have been extracted. The catalogue has been filtered using a range of inclination with a bias of 0.5° to take into account also possible perturbations. The worst cases scenarios are represented by the following altitude-inclination couples, as shown in Figure 2.1 and Figure 2.2:

- (900km, 83°)
- (1300km, 90°)

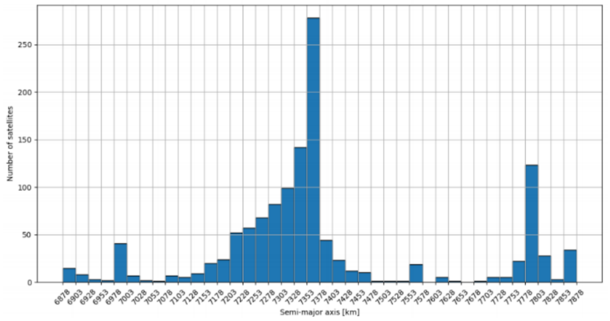

Figure 2.1: Distribution of semimajor axis for objects in orbits with inclination 83° +- 0.5°

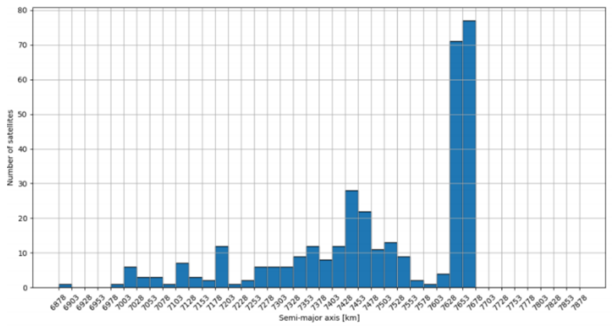

Figure 2.2: Distribution of semimajor axis for objects in orbits with inclination 90° +- 0.5°

Sun-synchronous orbits have a completely different behaviour because they are defined to have a specific orbital precession rate, while this constraint is usually ignored for other types of mission. If the right orbital altitude and inclination are selected, the precession rate matches the rate at which the Earth rotates around the Sun. Earth observation satellites are generally designed to have a fixed local time of 10.30am to maximise visibility conditions.

COLA analyses are performed in this study for a set of trajectories generated for the worst cases with a 10 minutes screening frequency over one full day of launch window. The propagation of orbits has been run for up to 3 days after the insertion in orbit and the maximum threshold separation for close approaches detection has been set to 25km. During the simulations, the coasting arc and the orbital insertion of the launch mission have been separately analysed, and the results merged into a single conjunction dataset.

Results show that the launch epochs raising more warnings of possible collisions for the worst-case scenarios are the following:

- 900km x 83°: 25/02/2020 15:50:00
- 1300km x 90°: 25/02/2020 04:50:00
- SSO orbits: 25/02/2020 10:30:00 (set by mission purpose)

The worst launch epochs extracted for each inclination have been, then, used as a baseline for the analysis of all the other altitude-inclination pairs. The results are reported in Figure 2.3.

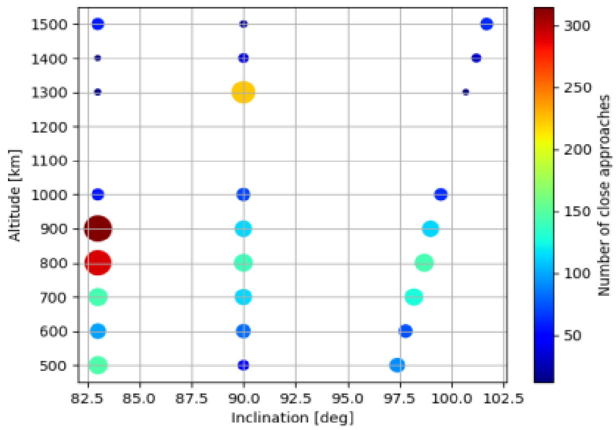

Figure 2.3: Number of events for the altitude-inclination couples at fixed launch epochs used for each inclination

The number of events plotted in Figure 2.3 are discrete, generated with a fixed time for each inclination. This implicates that if the launch is delayed or anticipated of just a few minutes, the scatter plot would be slightly different. E.g., during the successive minutes, a certain object might be more dangerous than the epoch defined before in a different orbital plane.

The outcomes of the two 1-day analyses on the two worst cases (900km, 83°) and (1300km, 90°) are reported in Figure 2.4 and Figure 2.5. The number of events detected changes substantially and a high-risk time range is evident. Despite the under sampled nature of the study, the trend is well reconstructed and a danger zone is easily distinguishable. Therefore a 10-minutes launch window screening rate might be helpful to screen a larger time range coarsely in the initial phases of the mission definition.

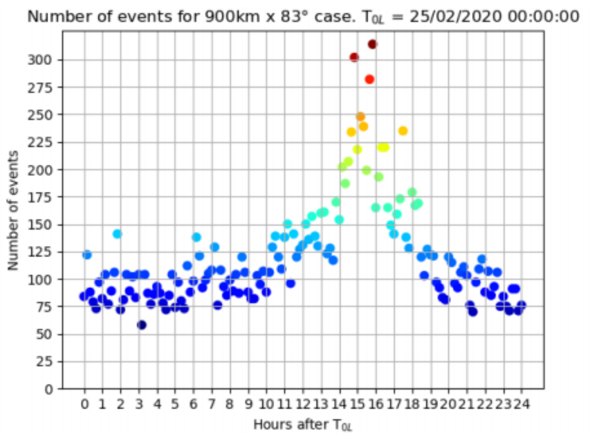

Figure 2.4: Number of events detected for the case 900km x 83°

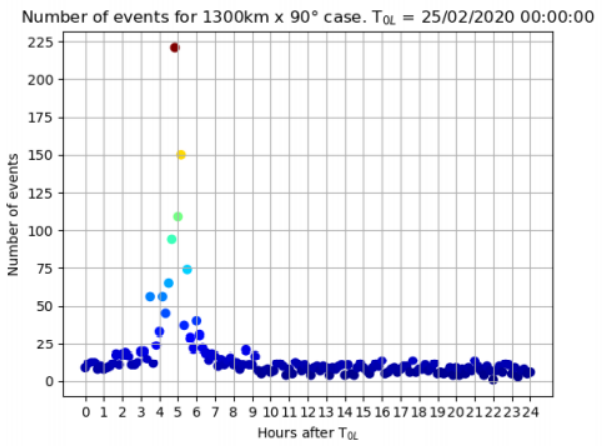

Figure 2.5: Number of events detected for the case 1300km x 90°

2.1 1300km x 90°

The orbital plane is generally set by fixing the inclination and the right ascension of the ascending node. Then, semimajor axis and eccentricity define the shape of the orbit in that plane, while the argument of perigee sets its orientation. The case 1300km x 90° outlines the biggest gap between the peak and the average minimum, so it will be taken as the baseline for this analysis.

Launching at the epoch in exam, the vehicle is going to be placed on an orbit plane with an $\Omega = 132°$ and $i = 90°$. The TLE catalogue has been used to retrieve the objects within the inclination of interest (89°-91°). According to the histograms in Figure 2.6 and Figure 2.7, objects within this range of inclinations are denser in the following zones:

- $300° < \Omega < 330°$
- $h \approx 1300km$

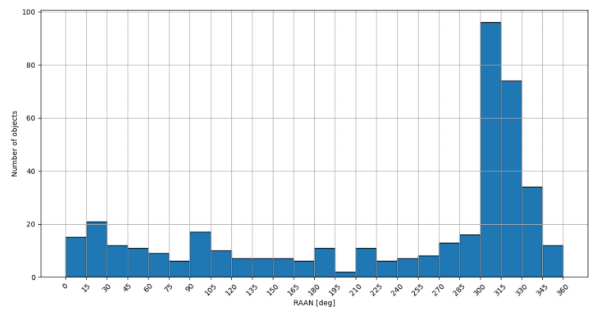

Figure 2.6: Distribution of objects with i = [89°,91°], in terms of right ascension of the ascending node

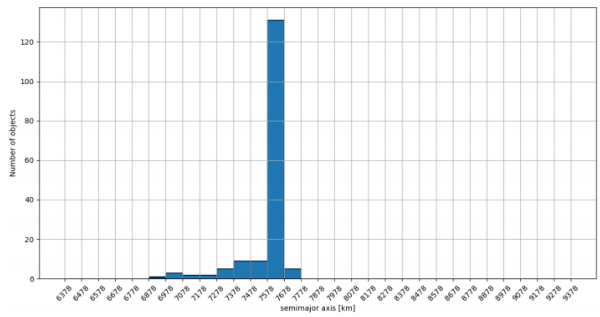

Figure 2.7: Distribution of objects with i = [89°,91°], in terms of the semi-major axis

The vehicle orbital plane is rotated of almost 180° with respect to the most crowded orbit area at the same altitude, which means a higher number of warnings of possible head-on collisions might be raised.

For the sake of completeness, the right ascension of the objects detected for the worst launch date is exactly within the range [300°-330°], as in Figure 2.8.

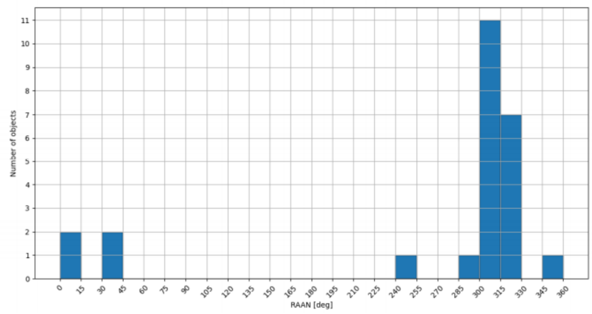

Figure 2.8: Ω of objects detected as possible encounters

Given that objects in space are not uniformly distributed, if the launcher is simulated to be launched every 10 minutes, because of the effect of the Earth rotation, it will be placed on an orbital plane that rotates its Ω of 2.5° every launch. This angular displacement causes a variation of number of warnings detected by the software accordingly to the most crowded areas in terms of right ascension.

2.2 900km x 83°

Similar results obtained in the previous section have been obtained for this case. Since the number of events detected for this scenario is considerably higher on average with respect to the (1300km, 90°) case, it is very suitable for performing high-frequency analyses, because more sensitive to small changes in launch epochs. For this reason, the next sections will be taking into account only this scenario.

3 SCREENING FREQUENCY

Being able to perform COLA with a launch window resolution of a few seconds can give important insights on the conjunction geometry and probability of collision variation. Since the MD approach is the least computationally intensive, it can be used to perform multiple preliminary screening of possible in orbits collision. For this reason, only MD algorithms are going to be used to define the most appropriate screening rate frequency on the launch window not to impact the accuracy of the results.

The scenario used for the entire study developed from now on is represented by the worst-case (900km, 83°). The reason for this choice can be found in the number of close approaches detected by the miss distance algorithm. Additionally, this scenario has the widest variety of objects' ID detected, which is helpful to generalize the investigation with as many different cases as possible.

The former analysis has used a screening frequency of 10 minutes over the entire launch window, while here the approach increases the resolution to time-steps of:

- 1-minute
- 10-seconds
- 1-second

Typically, when the chaser approaches the target, the distance decreases, tends to a minimum, and then increases again when the chaser moves away. This trend can be described as a parabola in which the minimum represents the minimum miss distance.

The detected events and their risk level will be defined in terms of miss distance for two different approaches:

- Fixed object ID
- Total number of events

3.1 Fixed Object ID

By fixing the object ID the elements within the scenario become only two: the target and the chaser. Data resulting from the miss distance algorithm has been filtered to gather only the events raised by the specific object, if any. The approach of creating multiple trajectories of the target by delaying or anticipating the time of launch gives the expected representation of the encounter with respect to the chaser.

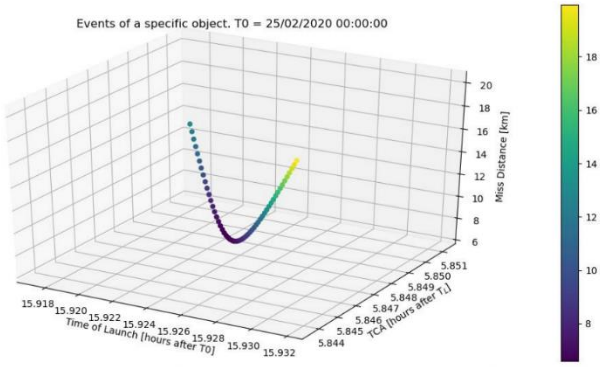

Figure 3.1: 3D Miss distance variation of a specific object in terms of time of launch and time of closest approach

A higher screening frequency on the launch window results in an increased knowledge of the nature of the close approach because the function is reconstructed with more samples. The Figure 3.1 represents the parabola of the approach in a 3D shape. Every dot represents an event detected by the software for that specific object, and every event is associated with a certain miss distance and time of closest approach. The miss distance in the example changes reasonably quickly in a very short time span, as shown by the steepness of the parabola. The third dimension, represents the time of closest approach (TCA), that changes accordingly to the time of launch (ToL).

3.1.1 1-minute screening

By performing a 1-minute screening on the test object ID 31414, the algorithm detects only one possible conjunction event with a miss distance less than 25km, as in Figure 3.2. Because of the single event detection, the knowledge of the approach is not very detailed and useful for the operators.

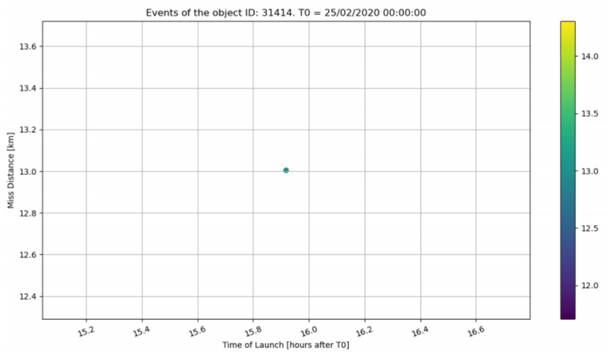

Figure 3.2: MD vs Time of Launch for the object ID 31414, 1-minute screening

3.1.2 10-seconds screening

Increasing the frequency to 10 seconds over the entire launch window, the shape of the parabola appears and the minimum miss distance decreases, meaning that the close encounter is better characterized, as in Figure 3.3. The knowledge of the close approach is increased and the object can be tagged as a real threat, since it is detected to be closer than previously identified, and it might raise operator's attention.

If uncertainties are considered this result can be transformed from a "mild" to a severe threat, or vice versa by the statistical analysis.

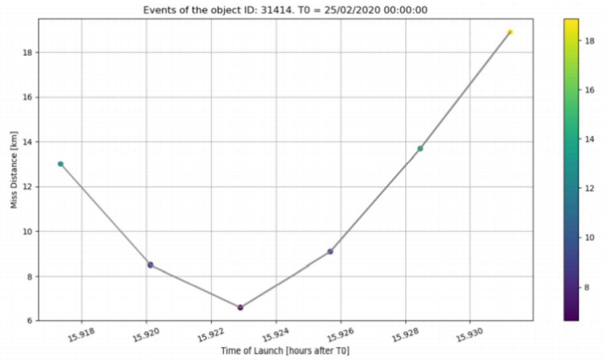

Figure 3.3: MD vs Time of Launch for the object ID 31414, 10-seconds screening

3.1.3 1-second screening

With a 1 second approach the shape of the parabola is very well defined, as in Figure 3.4. It is oversampled, because in this case it doesn't add any other information compared to the 10-seconds screening. In general, there is more possibility of characterizing the type of encounter by studying the steepness of the parabola, because we can also understand how quickly the approach is happening.

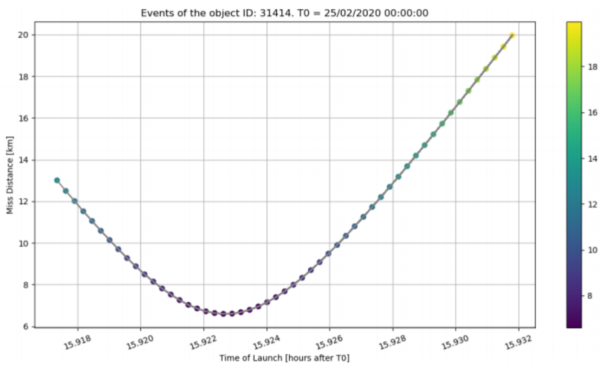

Figure 3.4: MD vs Time of Launch for the object ID 31414, 1-second screening

3.1.4 Fast approaching objects

It may happen that even the 10-seconds screening is not enough to reconstruct the pattern of the object, and a 1-second approach is needed, as for the case shown below in Figure 3.5. Here the algorithm can detect that fixed object ID only once. Considering that objects in space have an average velocity of 7km/s, in 10 seconds they travel about 70km, which is enough to completely miss the target and not appear in the outputs as a risky event.

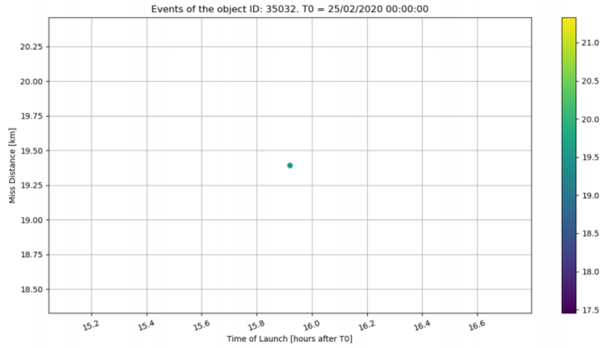

Figure 3.5: MD vs Time of Launch for the object ID 35032, 10-second screening

Fast-approaching objects can be potentially dangerous, and one of the main problems associated with the computation of the collision risk derives from the lack of knowledge on the orbital data accuracy. The TLE catalogue is not very accurate and does not provide an estimation of the accuracy of the orbit. When a conjunction event is detected and consequently associated with high risk, as in Figure 3.5, it is necessary to improve the knowledge of the orbital states of target and chaser through new tracking requests.

3.1.5 Periodical nature of the objects

Within the wide range of objects detected by the software, some of them show an interesting trend that recalls the periodicity of their orbits with respect to the target. These objects frequently raise warnings because of their dynamic and because the launcher is placed on different orbits at each time of launch.

In Figure 3.6, a 1-second screening frequency has been used. The object represents a danger when the launch happens at certain times, but there is also a range where the object disappears and it is not tagged nor as a threat nor as a warning anymore. That can be defined as a "safe zone" for the launcher to be launched to not encounter the specific object ID. However, since every delay of the launch date binds the target to be placed on a certain orbit plane due to the rotation of the Earth, the close encounter shows up again.

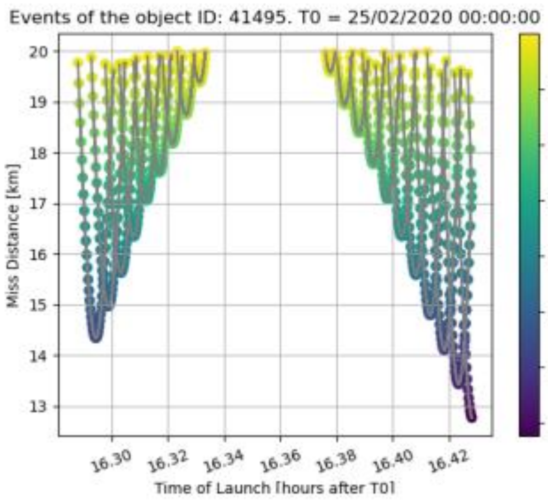

Figure 3.6: MD vs Time of Launch for the object ID 41495

The grey lines connecting the different dots reconstructs successive TCA epochs, which are closer than a few seconds. Some curves, even if on the same plane, are separated in time (time of closest approach) by minutes or even hours, so they would be spread through the third dimension of the plot, as in Figure 3.1.

3.1.6 Slope of the parabola

The variation of the miss distance with time has always a parabolic shape, because objects approach each other and then move away in a very short time span, due to their orbital velocities.

By studying the steepness of these curves through the use of the derivative of the miss distance with time of launch, it is possible to identify how fast the approach is occurring. A fixed object ID has been set and the miss distance algorithm has been run for a 10-minute launch window with a 1-second screening frequency. This resolution is necessary to have enough data to reconstruct the slope.

In Figure 3.7, the branch on the left side belongs to another orbit of the same object ID due to its periodic trend to re-encounter the target after a certain period. That branch is translated in TCA with respect to the main one that is being analysed.

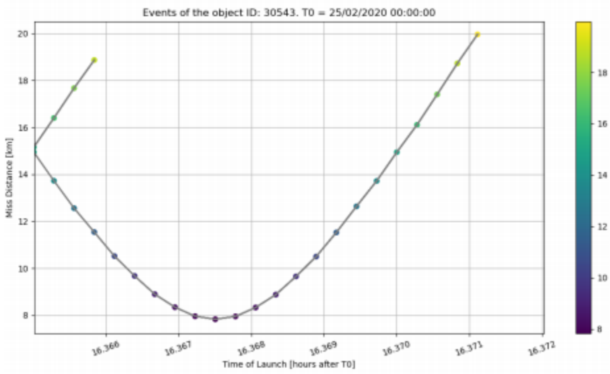

Figure 3.7: MD parabola for the object ID 30543

The slope of the parabola identified in Figure 3.8 for the object ID 30543 shows a moderately fast approach, evolving on a time span of 25 seconds.

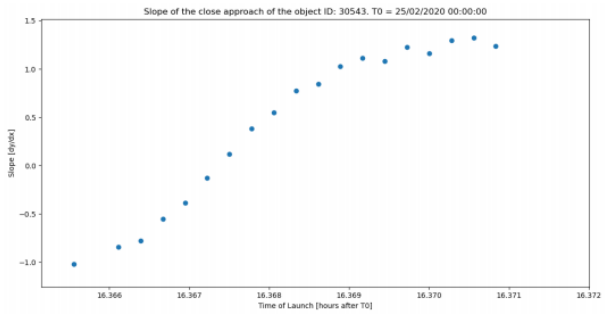

Figure 3.8: Slope of the parabola created by the object ID 30543

The most dangerous and unpredictable encounter would be represented by a slope with the shape of a step function. In this case the two objects approach so quickly that their miss distance reduces to a minimum instantaneously. This scenario does not represent the reality, but can be indicative to tune the danger of each object's approach by setting limits on its speed. In real world scenarios, the fastest approach is represented by retrograde orbits, cause of possible head-on collisions.

The outcome from the slope analysis can help the operator understand which of the approaches might be more dangerous in terms of relative motion and tag objects accordingly, in order to follow and detect the ones producing higher risks.

3.2 Total number of events

The general trend of number of events detected over the entire launch window is also affected by the screening frequency. The launch window is set to 10 minutes and the screening resolutions are the same as defined in the previous section. The mission profile investigated is only represented by the second phase of circularisation because the results from the suborbital arc show less than 90% of number of encounters found with respect to the second phase.

The analysis focuses on a short time range slightly after the time of maximum closest approaches detected for the first worst-case scenario (900km, 83°). In Figure 3.9 a 1-minute screening frequency has been used. The scatter plot has only few dots that describe the decreasing trend of the number of events detected by the software after the peak.

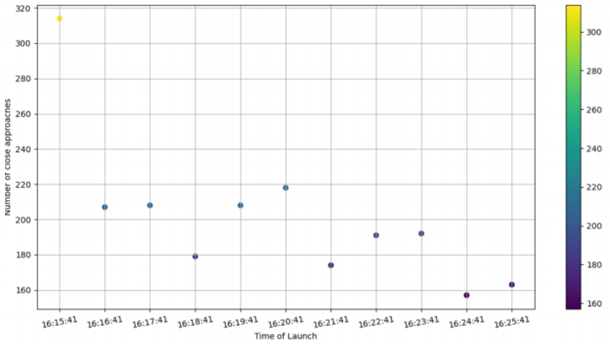

Figure 3.9: Number of close approaches - 1-minute step

However, increasing the sampling to 10-seconds refines the results, as shown in Figure 3.10, where more data has been retrieved and the curve is better characterized. The operator can choose the best launch window to minimise the number of warnings detected as much as possible while ensuring the safety of the mission launch among the different options he/she has.

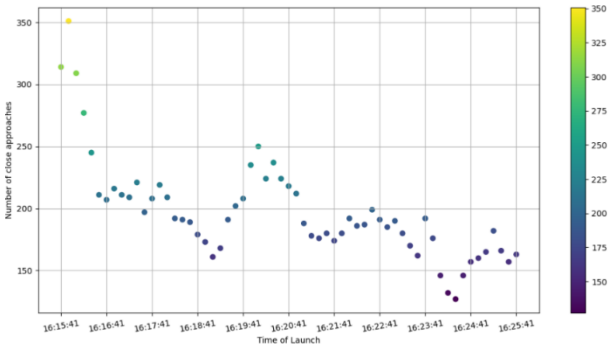

Figure 3.10: Number of close approaches - 10-seconds step

In Figure 3.11 a 1-second screening generates a curve that appears quasi-continuous, which is accurate, but does not add information to the trend of events detection when compared to the coarser 10-seconds screening. The increase in computational effort it is not worth the increase in accuracy.

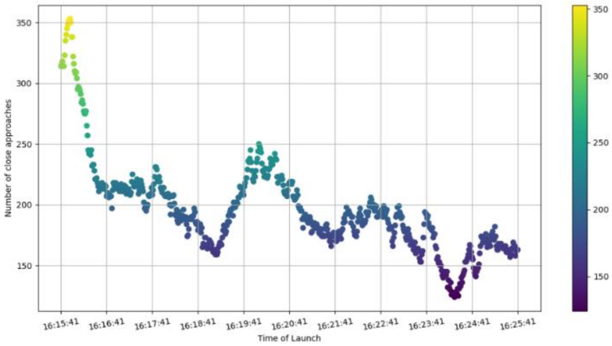

Figure 3.11: Number of close approaches - 1-second step

Apart from some particular cases, in the evaluation of the number of events the 10-seconds screening frequency is adequate to characterise the phenomenon.

4 EVALUATION OF SEVERITY OF EVENTS THROUGH STATISTICAL ANALYSIS

Conjunction analysis can be based on evaluating the miss distance between the possible colliders, but this approach does not take into account how reliable the orbits are. To consider the accuracy of the orbit determination, the uncertainty of each orbit must be considered. This way, the number of false alarms is reduced drastically when compared with the approach of issuing warnings based on miss distance threshold.

A detailed and complete analysis has been performed for the most prominent case resulting from the previous sections, in particular the worst-case scenario (900km, 83°). The severity of the occurring events has been evaluated to demonstrate how close the results are when statistical methods are employed compared to the basic miss-distance approach.

This analysis will consider the uncertainty resulting from the launch for the analysis of the collision probability of each encountered event, and the cumulated risk across the launch window.

To compute the probability of collision the launcher covariance matrix is required as an input. Since this would require a thorough analysis of a specific vehicle configuration, it is therefore assumed constant for all cases, with a sample matrix obtained from an object from the catalogue.

The computational time increases significantly when uncertainties are part of the analysis. The process to extract statistical data about the nature of the collisions requires in input a state vector and associated covariance, the algorithm then propagates for 3 days looking for possible collisions. The screening frequencies used here are:

- 1-minute step over 10 minutes of launch window

- 10-seconds step over the first minute of the previous launch window

4.1 1-minute screening

The first test has been conducted assessing conjunction events using a screening rate of 1 minute. The outcome is represented in terms of cumulative probability of collision in a logarithmic plot, illustrated in Figure 4.1. The blue bars represent the probability of collision, while the subplot shows the launch window status identified by three different colours: green, amber and red respectively for open, warning and closed launch opportunities.

As in [2], international best practices recommended to use a collision risk threshold of 10^{-6}, and a warning of one order of magnitude lower to identify risky instants. The machine epsilon (black line) gives an upper bound on the relative error due to rounding in floating-point arithmetic.

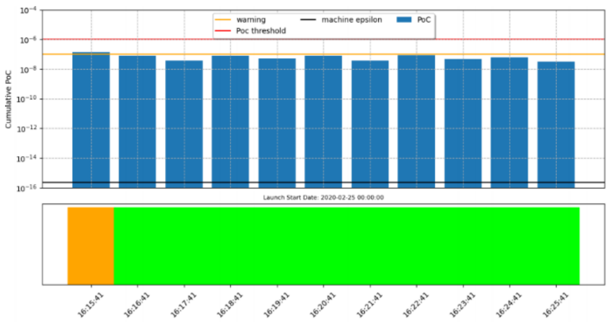

Figure 4.1: Cumulative PoC for COLA duration 72h and screening frequency of 1 minute

Despite the huge number of encounters evaluated by the miss-distance algorithm across the same time frame, most of the launch window is still available apart from the first minute. The threshold is high enough to leave access to that orbit open.

For some launch epochs, even when the MD analysis detected about 35% less encounters than the peak across the same time range of investigation (as in Figure 3.9), when involving covariances, the probabilistic method reported a change in PoC of less than 1 order of magnitude.

Additionally, the number of closest approaches detected by the MD analysis is resulted higher than the PoC one because it lacks of covariances information. Even if a larger number of events is detected, it might happen that most of them have a low probability of collision, participating only partially to the cumulative probability.

4.2 10-seconds screening

Launching during the first minute in Figure 4.1 might be dangerous because that epoch is tagged as "warning". Proceeding with the investigation about finding the "worst" case in this section, a 10-seconds screening over the first minute is provided.

Despite the more refined analysis, the results are not so different over the entire minute, as shown in Figure 4.2. The cumulative probability of collision is still quite uniform and it decreases slightly during the last 20 seconds. The reduction visible at the end of the first minute follows the trend of the output coming from the miss-distance algorithm in terms of the number of events detected, represented in Figure 4.3.

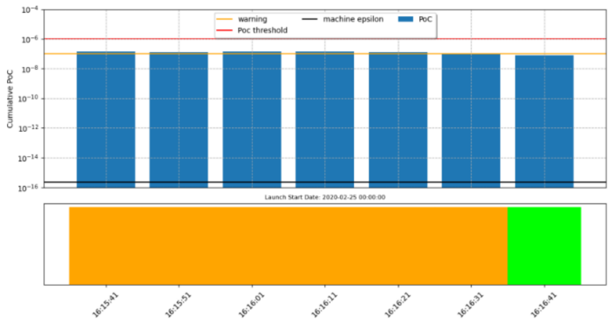

Figure 4.2: Cumulative PoC for COLA duration 72h and screening frequency of 10-seconds for the first minute

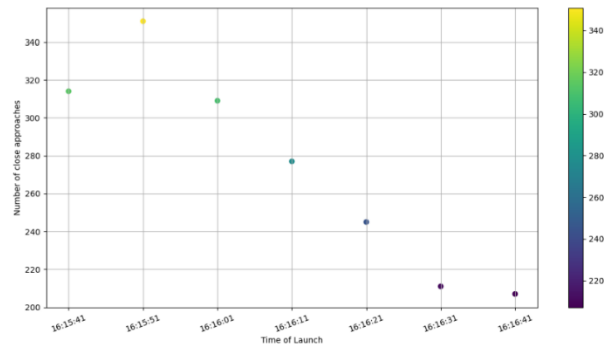

Figure 4.3: Number of close approaches – 1st minute with a 10-seconds screening frequency

5 CONCLUSIONS

The current study has answered questions regarding the identification of possible worst-case scenarios when launching from the UK, according to the range of accessible orbits from the launch site.

The presence of two actors in game (the target and the chaser) makes prediction on their relative motion hard to perform, in particular if the analysis is run on a large database of objects.

The worst-case scenario between the chosen dataset of orbits is represented by a specific case, analysed at the end of February 2020. Delaying or anticipating the date of the launch might change the distribution of the number of events detected across the entire grid of altitude-inclination combinations. In particular, for different ranges of inclination, new worst-case scenarios may appear. Moreover, many satellites belonging to future constellations are still in production and many others are not in the catalogue yet. Given the forecasted higher density of object in the following years, the same analysis may recognize different clusters in space, because of the fast-changing environment.

Results show that a 10-seconds screening frequency is sufficient across the launch window, to detect and characterize close encounters. However, for fast-approaching objects, for example in retrograde orbits, a 1-second frequency is necessary. Launching the vehicle into a retrograde orbit with respect to the most crowded region can increase the number of possible head-on collisions by orders of magnitude compared to other trajectories at the same altitude.

The conjunction event associated to a very short distance and fast approach needs probabilistic analyses to better characterise position uncertainties. For some launch epochs, even when the MD analysis detected about 35% less encounters than the peak across the same time range of investigation, when involving covariances, the probabilistic method reported a change in probability of collision of less than 1 order of magnitude. Despite the MD approach using higher margins for risk detection, the trend is comparable to the PoC. Improving methods such as MD could eventually lead to common use of analytical methods; reducing computational expense when compared to probabilistic methods.

6 REFERENCES

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2. Beaver, B. A., Hametz, F. M. E., Ollivierre, J. C., Newman, F. L. K., & Hejduk, M. D. (2015). Recommended Screening Practices for Launch Collision Avoidance. NASA/TM-2015-219270.