COLLISION RISK ASSESSMENT DURING LAUNCH AND INJECTION PHASES

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ABSTRACT

This paper presents the methodology currently used by CNES' Space Surveillance department to assess the collision risks during launch and injection phases. These analyses are critical to mitigate the chances of collision with the rest of the orbital population until the launched objects can be properly tracked. The article details how the collision risk assessment is performed and the simulation parameters typically used. It also focuses on a few key aspects to consider when performing this type of analysis (launch window sampling, uncertainty realism, etc.) and provides the rationale behind some important choices (risk criteria, etc.).

Keywords: collision risks; collision probability; launch phase; injection phase; LCOLA.

1. INTRODUCTION

As the number of objects in orbit rapidly increases, the risk of collision becomes even greater, not only in-orbit but also during launch and ascent. Launch Collision Risk Avoidance (LCOLA) has been routinely done for several decades now, but how it is performed varies. Originally, only a screening against manned missions (like the ISS) was done routinely. Candidate launch times were closed if the distance between these critical assets and the trajectory planned for the rocket body ever came below a given threshold (for instance, 200 km). Now, the screening is usually extended to the rest of the orbital population and often relies on methods that take into account the positional uncertainty of the objects, like the collision probability.

On the U.S. side, the 18$^{\text{th}}$ Space Control Squadron (SPCS) imposes a screening to any entity launching from an Air Force launch range [1]. Launched objects must respect a stand-off radius of 200 km for manned missions, 25 km for active satellites, and 2.5 km for debris. A screening based on the collision probability can be requested to complement the screening solely based on the relative distance. A launch trajectory is considered dangerous if this probability is greater than 10^{-5} for a conjunction. Screenings can be performed every minute, 30 s, 10 s, 5 s, or every second. Missions can perform additional screenings with other risk criteria, but it is not mandatory. As mentioned by Hejduk et al. [4], this is generally the case for Goddard Space Flight Center (GSFC) missions, but not for Jet Propulsion Laboratory (JPL) missions, because their launch windows are either very short or instantaneous. As far as we know, few information on how other agencies/entities manage LCOLA are publicly available.

This paper presents the methodology used by CNES' Space Surveillance department to screen for dangerous conjunctions in upcoming launches. Two distinct phases are considered: the launch phase and the injection phase. Here, the injection phase is defined as the period of time between the injection date and the first orbit determination process (after which the satellite is assumed to be tracked, and standard collision risk avoidance procedures apply). The paper is divided as follows. Section 2 details the methodology used to perform LCOLA simulation, while Section 3 focuses on the key simulation parameters (sampling of the launch window, risk criteria, etc.) and on issues that may arise during LCOLA simulations. Finally, Section 4 presents an example of LCOLA simulation for a geostationnary-transfer orbit (GTO).

2. LCOLA METHODOLOGY

A collision risks assessment for a launch or an injection phase consists in analyzing the trajectory of one or multiple primary objects at different dates to determine the safest and most dangerous slots of a given launch window. Although launch and injection phases have their own specificities, the methodology

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used to assess the risks remains largely the same. Multiple launch dates within the selected launch window are analyzed separately, each analysis aiming to determine the risks incurred by the launch or injection trajectory over a given MET interval (*Mission Elapsed Time*) with respect to the rest of the orbital population. This section presents the methodology currently used by CNES' Space Surveillance department to perform such an analysis (sampling of the launch window, launch/injection trajectories, risk criteria, risks computation, etc.).

Launch window sampling

The first step of the collision risk assessment is to select the launch dates to be analyzed. This is done by sampling the launch window at regular intervals (every minute, every second, etc.), as illustrated Figure 1 for the launch window $[H_0, H_0 + T]$. Note that the sampling step Δt must be chosen carefully, as it can significantly impact the reliability of the analysis. This point will be further discussed in Section 3, once the methodology used has been fully introduced.

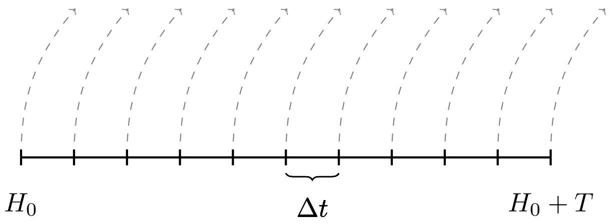


Figure 1: Sampling of the launch window.

Open and closed windows

Once a risk analysis has been performed for the selected launch dates, the computed data is used to determine the safe and dangerous parts of the launch windows, also referred to as the open and closed windows. As illustrated on Figure 2, launch dates that are deemed dangerous — represented by red arrows — will close the launch window between them and the adjacent launch dates. Consequently, only the parts of the launch window that are between two safe launch dates are open. The rationale here being that detected risks are not limited to a specific launch date, and that it is safer to consider they also apply to nearby launch dates that were not actively checked.

This already highlights the need to carefully select the sampling step. While smaller steps provide a finer resolution on the open and closed windows, the reliability of the risk assessment can become questionable when the sampling step is too large: dangerous parts of the launch window might be completely missed and incorrectly left open.

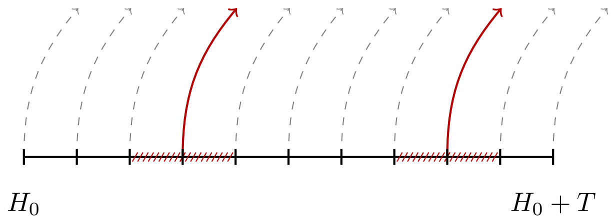


Figure 2: Open and closed windows.

Exploitable windows

Because of operational constraints, open windows are sometimes considered as unusable if they are too short. Therefore, the concept of exploitable windows is used to complement the open/closed windows: an open window is deemed exploitable when it exceeds a given duration (1 min or 10 min, for instance). This duration is usually defined by the operator in charge of the launch.

Launch/injection trajectories

Data for the primary objects are usually defined for a fixed launch date H_0 (which may or may not be included in the launch window considered for the analysis). For launch phases, state vectors and covariance matrices ephemerides are provided by the operator. For injection phases, the trajectory is defined by a state vector and covariance matrix at the injection date, which must be propagated over the analyzed MET interval.

To perform the risk assessment, this data defined at H_0 must be transformed in order to obtain the trajectory of the primary objects at each of the analyzed launch dates. Since rocket bodies are mostly subject to thrust forces during launch phases, their trajectories are assumed to remain unchanged in ITRF. Alternatively, the trajectory at another launch date can be obtained by a simple rotation in the equatorial plane of the appropriate Earth-centered frame (CIRF). In this frame, the rotation to be applied is the Earth Rotation Angle (ERA) or the sidereal time between the initial launch date and the new launch date. The covariance matrices are assumed to remain unchanged in a given local orbital frame, such as TNW.

During injection phases, orbital dynamics forces are predominant and can change significantly over the duration of the launch window. Consequently, the trajectory of the satellite must be recomputed at regular intervals to properly account for these forces (ideally, for each of the analyzed launch dates). Similar to launch phases, the initial state vector and covariance matrix are assumed to remain unchanged in ITRF and in a local orbital frame, respectively. Note that the initial covariance matrix is propagated through a simple state transition matrix, and that the uncertainty is assumed to remain normally distributed at all times. As discussed in Section 3, this is not always a valid hypothesis, especially for long MET intervals.

For the secondary objects, a catalog of state vectors and covariance matrices ephemerides for the tracked objects is generally used (like the SP ephemerides). TLE catalogs are also supported but are not often used in practice, since they contain data of poorer quality and do not provide information on the positional uncertainty of the objects.

Risk criteria

The risk criteria used for the analysis have a major impact on the computed results and on the open/closed windows obtained. Our methodology currently uses the following criteria: the relative distance between the nominal position of the objects, the maximum and cumulative collision probabilities over the entire MET interval, and the Mahalanobis distance.

The relative distance is the most straightforward. It defines a spherical safety volume around the primary object and any object that crosses it during the analyzed time span is considered dangerous. It does not account for the positional uncertainty of the objects, which can be very large during launch and injection phases. This criterion is mostly used for critical assets like manned stations/objects but may also be used for other objects, like payloads or debris with a lower risk threshold. However, it can quickly become very restrictive.

For a given launch date, the maximum and cumulative collision probabilities are derived from the collision probabilities computed for the close encounters occurring in the analyzed MET interval (that is, each local minimum of the relative distance). These probabilities are computed under the classical short encounter hypotheses (rectilinear relative movement, constant relative speed, etc.), using the method proposed by Serra et al. [8, 9]. Assuming the computed probabilities are independent, the cumulative probability is then defined as follow:

$$P = 1 - \prod_{i=1}^{n} 1 - P_i, \tag{1}$$

with P_i the collision probability computed for a given conjunction and n the total number of conjunctions found. A launch date is considered dangerous if the maximum or cumulative probability exceeds a given threshold (for instance, 1E-5).

The computation of the k_p/k_s probability, or scaled PoC, is also supported [6]. This probability is obtained by applying various scaling factors on the covariance matrices of the objects (a different factor being applied to each matrix) and selecting the worst collision probability. A domain typically scanned for the k_p/k_s factors is $[0.25, 4] \times [0.25, 4]$. The method used to compute the collision probability for a given $(k_p,\ k_s)$ pair remains the same.

The last of the supported risk criteria is the Mahalanobis distance. It is the distance between the two objects expressed in terms of positional uncertainty and is defined as:

$$d_m = \sqrt{\vec{\mu}^T\ \mathbf{C}^{-1}\ \vec{\mu}} \tag{2}$$

where $\vec{\mu}$ is the relative position and $\mathbf{C}$ is the combined positional uncertainty. An object is considered as dangerous if the Mahalanobis distance is lower than a given threshold (for instance, 3σ). Effectively, this risk criterion defines a time-dependent, ellipsoidal safety volume around the primary object, that is based on the positional uncertainty of both objects. Since these uncertainties can grow significantly during launch and injection phases, it can be very restrictive.

Remark 1: *Instead of the Mahalanobis distance, it could be interesting to define a similar ellipoidal safety volume for each object, and to check if these volumes intersect. However, this is not currently implemented.*

Risks computation

The method used to identify the dangerous parts of the MET interval for a given launch date depends on the risk criteria. For the relative distance and the Mahalanobis distance, the MET interval is sampled at regular intervals to detect any change of sign of risk function's derivative that would correspond to a local minimum. If that is the case, a standard iterative root finding algorithm is then used to find this local minimum and to identify the time period where the risk function (i.e. the relative distance or the Mahalanobis distance) is below the selected risk threshold. Note that the time step used when checking for possible changes of sign must be small enough to properly capture the variations of the risk function: each subinterval is assumed to contain at most a single local extremum. An adaptive step is used to automatically reduce this time step when large variations are detected.

For the 2D and k_p/k_s collision probabilities, the risk criterion is an amalgamation of the individual probabilities computed on the MET interval. For a given pair of objects, a probability is computed at each local minimum of the relative distance, which are found using the method described above.

Note that the risk computation can be performed in parallel, since each launch date can be analyzed independently.

Prefiltering of the orbital population

Because computing the risks for every secondary object over the entire window can be time-consuming, the secondary objects are usually prefiltered to eliminate the ones that are clearly not dangerous. This is done in a similar way to the screenings performed daily on the orbital population: after choosing an appropriate safety distance, specialized algorithms are used to quickly identify the secondary objects that cannot come close to a primary object. In a LCOLA context, this can be done by applying standard sieves at each launch date, like a variant of the altitude filter initially proposed by Hoots et al. [5] or the smart sieve proposed by Alarcón et al. [2].

However, an alternative filter specifically designed for launch phases is used instead. This filter relies on an iterative process that periodically splits the launch window, MET interval, launch trajectories and orbital trajectories into smaller parts and applies different subfilters to determine and refine the parts of the launch window and MET interval deemed dangerous for each pair of objects. These subfilters include an altitude filter, a filter on the height w.r.t. the equatorial plane, a time filter and a right ascension filter. Since this filter provides the dangerous parts of the launch window and MET interval for each pair of objects, this can significantly reduce the computation required for the risk analysis by eliminating large chunks of the launch window.

Regardless of the filter used, note that the safety distance used for the prefiltering of the secondary objects must be chosen carefully. If the relative distance is used as the risk criteria, it is straightforward. However, that is not the case for other risk criteria, in particular for the Mahalanobis distance. In that case, the safety distance must be large enough to ensure no risk can possibly be missed, which usually requires to analyze the covariance matrices of the primary and secondary objects beforehand to select a safety distance that contains the largest possible ellipsoidal safety volume. For the collision probability, the safety distance must be large enough to ensure the probabilities that would have been computed for the filtered objects are negligible.

Open/Closed windows visualization

The results of a LCOLA simulation typically include the computed risk intervals and the open and closed parts of the launch window for different risk criteria. These open/closed windows are vizualized in the form of a chronogram. Figure 3 is an example such a graph. The open windows of more than 30 s are shown in green for different risk thresholds. This presents the evolution of the exploitable windows in a synthetic way, which allows to immediately identify the safest parts of the launch window. For this example, most of the launch window is left open when a threshold of 10^{-6} on the cumulative collision probability is used. However, launch opportunities start to diminish significantly if this threshold is lowered to 10^{-7}. The parts of the launch windows closed because of a risk with the ISS or CSS are also shown on the first line, in red. Since these are critical assets, this highlights the parts of the launch window that should be absolutely avoided.

3. LCOLA SIMULATION PARAMETERS AND CHALLENGES

Now that the risk analysis process has been described, this section focuses on the LCOLA simulations themselves, discussing the motivation behind some parameter choices and some of the challenges typically encountered.

Launch window sampling

As mentioned in Section 2, the step used to sample the launch window must be chosen carefully. According to Hejduk et al. [4], most launches are *launch-on-minute* (i.e. only even minutes in the launch window are candidate launch times), some are *launch-on-30s* and a few are *launch-on-second*. This characteristic already sets the minimum precision required for the sampling, as all candidate launch times must be investigated. However, using a finer step provides a better resolution for the open closed/windows, as any launch date deemed dangerous will close the adjacent parts of the launch window.

Additionally, problems may arise if the sampling step is too large. Since open windows are defined as the parts of the launch window that are between two safe launch dates, it is assumed the sampling step is small enough to properly capture the evolution of the risks over the launch window. If this step is too large, risks for intermediate launch dates might be missed and parts of the launch window might be left open when they should not. However, reducing the sampling step can have a steep computational cost. Therefore, a compromise must be reached to ensure the computational time remains compatible with the

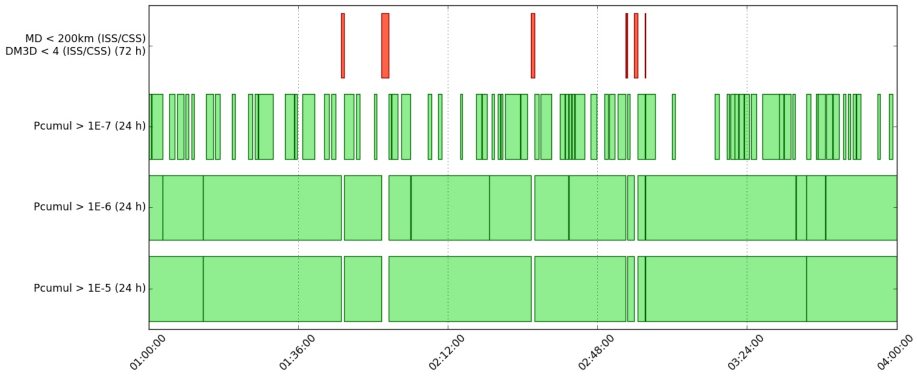


Figure 3: Example of a typical chronogram used to visualize the open/closed windows.

operational timetables, while limiting the chances of missing dangerous launch dates.

In practice, we are using a step of 1 s to sample the launch window. This choice is based on empirical studies done on a few launches: a step of 1 min was not deemed acceptable since many risks were missed, and even a step of 10 s was not always enough. There is of course no guarantee that no risk will be missed with a step of 1 s, but this should be a rare occurrence, and parts of the launch window incorrectly left open will have a limited duration. Moreover, reducing the sampling step further is generally too costly in terms of computational time, especially for long launch windows.

If launch opportunities are guaranteed to be limited to fixed dates (like *launch-on-minute*, for instance), the analysis could focus only on these dates and on nearby launch dates (to be on the safe side). However, this is not supported by our software at the moment and the entire launch window is systematically analyzed.

Risk criteria

The risk criteria are among the most impactful parameters of a LCOLA simulation but remain a relatively open choice for both the risk function (relative distance, max/cumulative collision probability, Mahalanobis distance) and the risk threshold. If very restrictive criteria are used to ensure the chances of a collision to occur are minimal, the launch window will be mostly closed, which will impede the operations. Of course, arbitrarily relaxing the risk criteria to avoid closing parts of the launch window is not acceptable either. A balance between the two must be found.

In practice, multiple risk criteria are often used conjointly, and the risk thresholds used depend on the objects considered (manned mission, payloads, debris, etc.). A threshold on the cumulative collision probability is usually applied to all objects and is sometimes complemented by other risk criteria. For instance, a safety distance of 200 km is used for manned missions, since they are the most critical assets in orbit. Moreover, a screening duration of at least 72 h is required due to the LOS regulation [3]. For other objects, a threshold on the relative or Mahalanobis distance may also be applied. Typical thresholds are 10^{-5} or lower for the cumulative collision probability, 5 to 25 km for the relative distance, and 2 to $3\,\sigma$ for the Mahalanobis distance. These thresholds are specific to each mission, since they depend on the characteristics of the mission (launch or injection phase, risk tolerance of the operator, traversed orbital regimes, etc.).

LCOLA simulations often include the results for different combinations of risk thresholds. For instance, the open/closed windows obtained for a threshold of $10^{-7}, 10^{-6}$ and 10^{-5} could be compared. This provides insight into how the open/closed windows evolve when relaxing the risk criteria and gives more flexibility when choosing a safe launch date. If the launch window is mostly closed initially, a relaxation of the risk criteria can be considered while still avoiding the most dangerous parts of the launch window.

It is important to note the way collision risk analyses are performed for launch and injection phases is far from being standardized. As mentioned in the introduction, the 18^{th} Space Control Squadron (SPCS) [1] imposes a stand-off radius of 200 km for manned missions, 25 km for active satellites, and 2.5 km for debris. A screening based on the collision probability can be requested to complement this first screening, but it is not mandatory. If that is the case, a launch trajectory is considered dangerous if this probability is greater than 10^{-5} for a conjunction. However, Hejduk et al. [4] mention it is not rare for missions to also request/perform screenings with their own risk criteria.

Their report also presents several studies related to the selection of an appropriate collision probability threshold. One of the conclusions of these studies states that a threshold of 4×10^{-7} can be used with SP ephemerides while keeping between 50 to 80 % of the launch window open, at least for the cases studied (comprised of historical launches). Another study concludes that using a threshold of 5×10^{-6} is functionally equivalent to doing nothing from a risk management standpoint, and that a threshold of 6×10^{-8} is required to reduce the risk by a full order of magnitude. However, such a low risk threshold is not applicable in practice, as it generally results in the closure of most of the launch window.

Injection trajectories

As mentioned in Section 2, the trajectory of the objects placed in orbit must be recomputed for each launch date for injection phases. This is because orbital forces (central and third-body attraction, drag, solar radiation pressure, etc.), which are time-dependent, are now predominant instead of thrust forces. However, depending on the size of the launch window and MET interval, and on the step used to sample the launch window, systematically propagating the initial state vector and covariance matrix for each launch date can become time consuming.

To reduce the computational time dedicated to this propagation, an option is to consider the trajectory computed for a given launch date approximatively constant in the appropriate Earth-centered frame (ITRF) for a limited duration. Which duration is acceptable from a risk analysis standpoint depends on the trajectory studied and on maximum propagation time considered. As an example, table 1 lists the error observed when this approximation is used on a GTO trajectory. The first column contains the shift ΔH_0 applied to the initial launch date, and the other columns contain the deviation from the actual trajectory at different propagation times (24 h, 48 h, and 72 h). As we can see, the error increases rapidly with ΔH_0 and the propagation time. Since the positional uncertainty during an injection phase can be significant, a ΔH_0 of 1 min might be viable if the MET interval is not too long, but such an approximation should be used with care.

Table 1: Error in position when considering a propagated trajectory fixed in ITRF for a duration ΔH_0.

$\boldsymbol{\Delta H_0}$	**MET**		
	24h	48h	72h
2 min	1 km	10 km	25 km
5 min	2 km	25 km	60 km
10 min	4 km	50 km	120 km

Uncertainty realism

The process described so far assumes the uncertainty on the position of the objects is properly represented by the covariance matrices associated with each object. The implicit assumption here is that the positional uncertainty has a normal distribution and is centered on the nominal trajectory of the objects. While this hypothesis is routinely used for in-orbit objects, its validity can sometimes be questioned. This hypothesis is even more questionable for launch and injection trajectories.

Launch trajectories are usually provided directly by the operators and it is difficult to assess their realism. In their report, Hejduk et al. [4] attempted to do so for several historical launches, by comparing the predicted trajectories and the associated positional uncertainty to the GPS trajectory reported during the actual launch. For the studied launches, it concluded that the positional uncertainty of the launchers was actually well represented by the predicted data — despite the size of the covariance matrices — and that this data could be used for the collision risk assessment. Based on this conclusion, and having no meaningful way to verify the data provided by the operator, it is generally assumed that the uncertainty on the rocket bodies is well represented by this data.

Injection phases are different, since the operators typically provide the predicted state vector and covariance matrix at the injection point, which are then propagated over the MET interval. While there is no reason to question the realism of this data, the initial positional uncertainty can be much larger than the one yielded by a standard orbit determination (OD) process. As a result, it can grow quite significantly over time, to the point where the propagated uncertainty is no longer realistic: a simple covariance matrix cannot faithfully represent the actual uncertainty anymore, which affects the reliability of the screening process. This is currently the main limitation when performing a collision risk assessment, as there can be tens of hours between the injection date and the date the first OD process is expected to take place.

A more faithful representation of the propagated uncertainty could be obtained by using Taylor differential algebra, Gaussian mixtures, or similar methods, but the covariance matrices would remain quite large (possibly thousands of kilometers). The collision probability will still be impacted by the dilution phenomena and likely underestimated. And other risk criteria like the relative distance and Mahalanobis distance (or something equivalent if the uncertainty is not Gaussian anymore) will be extremely restrictive.

4. LCOLA EXAMPLE FOR A GTO ORBIT

This section presents an example to illustrate how a collision risk assessment would be performed for a satellite that will be placed on a geostationnary-transfer orbit (GTO). The mission plan is to inject the satellite a few moments after its perigee, at an altitude of 1000 km. The perigee and apogee of the orbit are at an altitude of 300 km and 50 000 km, respectively. In this scenario, the launch window considered lasts 3 h and an OD process is expected to take place within 10 h after the injection date.

Simulation parameters

For the simulation presented here, a step of 1 s is used to sample the launch window. A safety volume of 200 km is applied to manned stations (ISS and CSS). Additionally, periods resulting in a Mahalanobis distance below $4\,\sigma$ are also considered dangerous. For other objects, launch dates with a cumulative collision probability higher than 10^{-7} or 10^{-6} are considered dangerous.

The study is performed for two MET intervals starting at the injection date and lasting a total of 10 h and 16 h. Since unforeseen events might lead to a delay in the OD process, extending the MET interval initially considered by a few hours allows to select a launch date that further reduces the risks. However, each MET interval is still analyzed independently in case the additional risks limit the launch opportunities too much.

Lastly, small debris (i.e. objects listed as "SMALL" in the SATCAT) are excluded from the analysis to ensure simulation times are compatible with operational timetables and to avoid closing portions of the launch window because of objects that are less dangerous and potentially poorly tracked.

Analysis of the injection trajectory

Before proceeding with the LCOLA simulation, a typical first step is to perform a quick analysis of the nominal trajectory of the primary object. For instance, Figure 4 shows the altitude of the object for a few hours after the injection date. Since the orbit has a period of 15 h and 28 min, it takes a little less time than that for the object to cross the low-Earth orbital regime again. If the OD process can indeed take place within the first 10 hours, the risks should remain limited since the most populated altitudes will be avoided. However, the object will definitively traverse this orbital regime in the following hour, which will likely generate many risks. As a result, launch opportunities are expected to be notably reduced when the extended MET interval is considered.

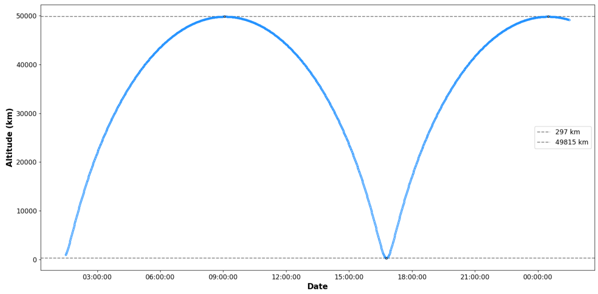


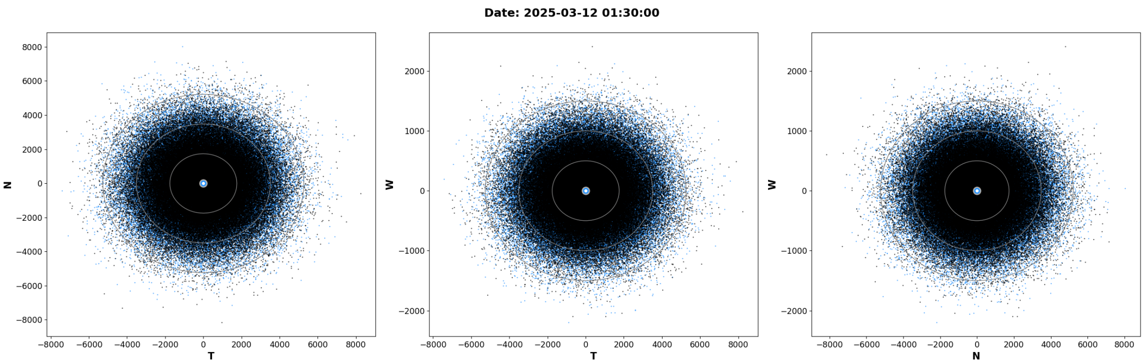
Figure 4: Altitude plot over the screening interval.

Analysis of the propagated uncertainty

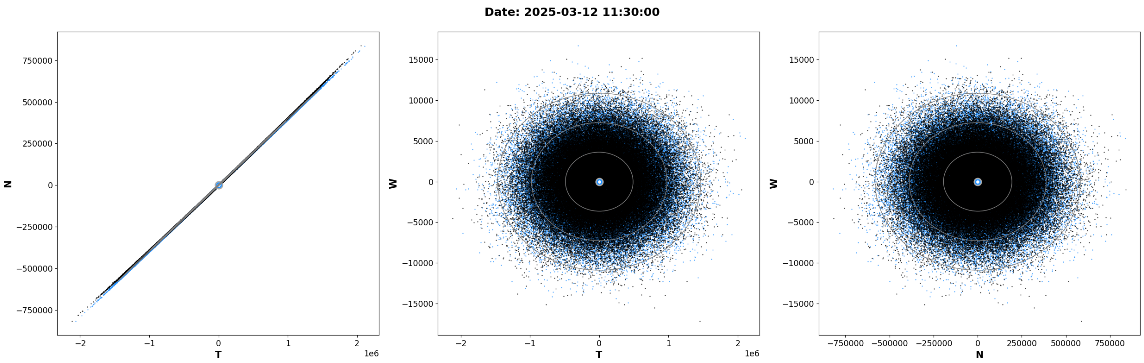
Another important preliminary step when performing this kind of LCOLA analysis is to analyze the propagated uncertainty over the studied MET interval. As mentioned in Section 3, the initial uncertainty can be relatively large and it keeps growing when propagated. At some point, the uncertainty will not be normally distributed anymore and a simple covariance matrix will not be enough to represent it faithfully. Therefore, it is critical to assess whether this happens during the analyzed time span.

This can be done by perturbing the initial state vector and propagating each of the generated samples separately (Monte Carlo propagation), and comparing them to covariance matrix propagated through a state transition matrix (STM propagation). Figure 5 shows such a comparison for the current scenario, in TNW. The samples resulting from the Monte Carlo propagation are plotted in black, and the samples generated from the propagated covariance matrices are plotted in blue. The initial uncertainty is shown in Figure 5a, and the uncertainty after 10 h, 11 h and 16 h of propagation is shown in Figures 5b, 5c, and 5d, respectively. As we can see, the initial uncertainty is already several kilometers wide, and it grows by multiple orders of magnitude in only a few hours. The uncertainty is still normally distributed during the first 10 hours, but the gaussianity starts to break down noticeably afterward. After 16 h (and even before), the uncertainty spreads along the curvature of the orbit and the covariance matrix is not enough to model this behavior.

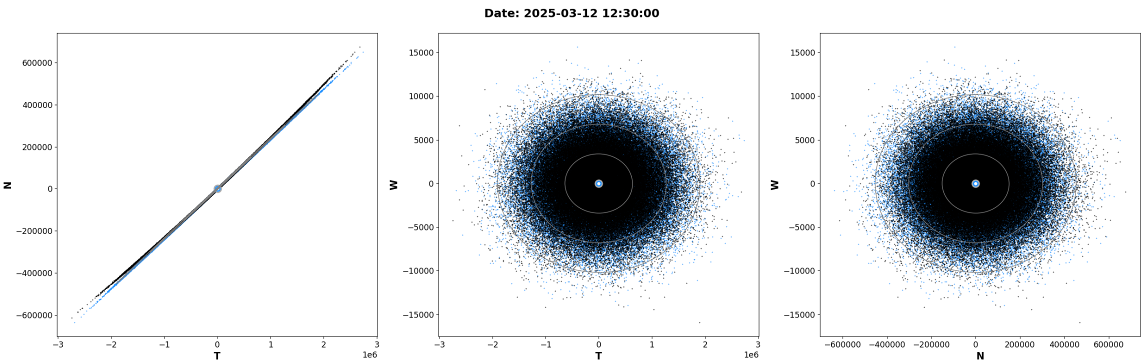
Given the results of this preliminary analysis, a MET interval of 10 h can be safely analyzed. However, the results obtained for the extended MET interval of 16 h should be considered with care because of the poor representation of the uncertainty.



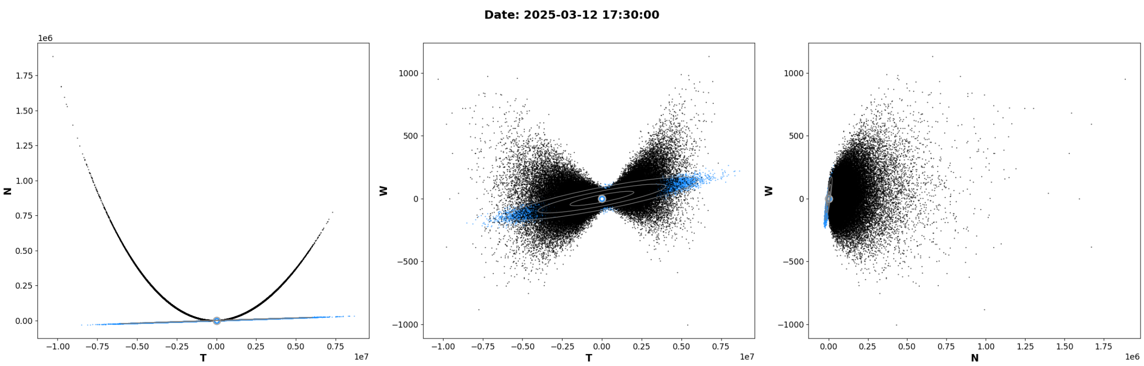
(a) Initial TNW uncertainty



(b) TNW uncertainty after 10 h



(c) TNW uncertainty after 11 h



(d) TNW uncertainty after 16 h

Figure 5: Positional uncertainty in TNW at injection and 10 h, 11 h and 16 h after injection [m]. The samples obtained by a Monte Carlo propagation are represented in **black**. The samples obtained from the propagated covariance matrix are represented in blue.

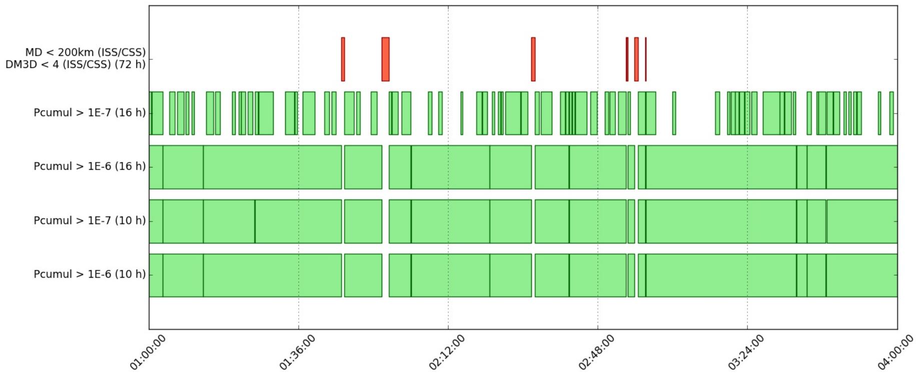


Figure 6: Chronogram obtained for the studied GTO injection.

Operational considerations

In an operational context, test runs are usually performed daily during the week preceding the launch to ensure no unforeseen problem occurs. These test runs also provide insight into the number of risks to expect and their impact on the open/closed launch windows. During this period, the risk criteria can be fine tuned in agreement with the operator if they are deemed too strict or too lax.

Because launches can sometimes be postponed at the last minute, backup launch windows are also often studied in parallel. The goal of these additional analyses is to provide some flexibility to the operators. If the new launch window is too close to the initial window to guarantee a new risk assessment can be performed in time (for instance, if the launch window is postponed to the next day), it has at least been preanalyzed beforehand. If time permits, the new window will still be reanalyzed closer to launch, with more recent data.

Open/closed windows analysis

Figure 6 shows the chronogram obtained from the LCOLA simulation. The top row displays the closed windows due to a risk with the ISS or CSS (in red). Other rows display the open windows for a given threshold on the cumulative probability (10^{-6} or 10^{-7}) and MET interval (10 h or 16 h). Only open windows lasting more than 30 s are displayed.

As expected, the launch window is mostly open when the propagation time is limited to the first 10 hours. Since the satellite has not yet traversed the most populated orbits, there are few risks and a threshold of 10^{-7} on the cumulative collision probability is not restrictive. As mentioned, using a screening duration of 16 h is questionable because of the poor representation of the positional uncertainty. However, let's assume for the sake of discussion that this uncertainty is well represented here. Although the launch window remains mostly open when a threshold of 10^{-6} on the collision probability is used, we see that lowering it to 10^{-7} notably reduces the launch opportunities. The satellite has now traversed the low-Earth orbits, which naturally increases the chances of collision.

Given these results, the recommendation would be to prioritize launch dates that satisfy the most restrictive criteria (cumulative probability lower than 10^{-7} and 16 h-long MET interval). If that is not possible, the recommendation would be to still use a threshold of 10^{-7} on the cumulative probability, but to fall back on the initial screening period of 10 hours. Of course, the parts of the launch window closed by the ISS/CSS must be avoided at all cost.

5. CONCLUSION

This paper has detailed the methodology currently used by CNES' Space Surveillance department to perform LCOLA simulations. Future works will explore ways to remediate some of its limitations. In particular, while using a step of 1 s to sample the launch window limits the chances of missing dangerous conjunctions and provides more precise open/closed windows, it also significantly increases the computational time of the simulations. An alternate approach was presented by Oltrogge and Alfano [7] in a recent paper. Their method is a topology-based approach that provides a more continuous analysis of the launch window, instead of analyzing fixed launch dates and extrapolating the conclusions to nearby launch dates. Although the article does not fully detail the methodology used, this approach seems interesting.

The problems related to the uncertainty realism are also a major limitation when screening for dangerous conjunction during early-orbit phases. After some time, the positional uncertainty is poorly represented by the propagated covariance matrices and the reliability of the screening process becomes questionable. The ability to faithfully model the uncertainty over longer periods of time would be very valuable, as it would allow the injected satellite to be systematically covered until they can be tracked. Taylor Differential Algebras (TDA) are of particular interest for this. However, their application in a LCOLA context is not straightforward. Beside the implementation cost, the computation of the collision probability will be significantly impacted (since the uncertainty is possibly not gaussian anymore), and a TDA method will likely have to be coupled with a Gaussian mixtures method or similar.

REFERENCES

[1] 18th SPCS. *Launch Conjunction Assessment Handbook*. 18th Space Control Squadron, 2018.

[2] J. R. Alarcón Rodríguez, F. Martínez Fadrique, and H. Klinkrad. "Collision Risk Assessment with a 'Smart Sieve' Method". In: *Joint ESA-NASA Space-Flight Safety Conference*. Ed. by B. Battrick and C. Preyssi. Vol. 486. ESA Special Publication. Aug. 2002, p. 159.

[3] *Arrêté du 31 mars 2011 relatif à la réglementation technique en application du décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales*. May 2011. URL: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000024095828/2024-07-13.

[4] Matthew D. Hejduk et al. *Launch COLA Operations: An Examination of Data Products, Procedures, and Thresholds*. 2014. URL: https://ntrs.nasa.gov/citations/20150015576.

[5] Felix R. Hoots, Linda L. Crawford, and Ronald L. Roehrich. "An Analytic Method to Determine Future Close Approaches between Satellites". In: *Celestial mechanics* 33.2 (June 1984), pp. 144–158. ISSN: 1572-9478. DOI: 10.1007/BF01234152.

[6] François Laporte. "JAC Software, Solving Conjunction Assessment Issues". In: Advanced Maui Optical and Space Surveillance Technologies Conference. 2014, E4.

[7] Daniel L. Oltrogge and Salvatore Alfano. "Innovative LCOLA Tool Prioritizing Accuracy, Launch Access and Efficiency". In: 2021.

[8] Romain Serra. "Opérations de Proximité En Orbite : Évaluation Du Risque de Collision et Calcul de Manoeuvres Optimales Pour l'évitement et Le Rendez-Vous". Theses. INSA de Toulouse, Dec. 2015.

[9] Romain Serra et al. "Fast and Accurate Computation of Orbital Collision Probability for Short-Term Encounters". In: *Journal of Guidance, Control, and Dynamics* 39.5 (May 2016), pp. 1009–1021. ISSN: 1533-3884. DOI: 10.2514/1.g001353.