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Operational Concepts and Design of Mitigation Actions for Collision Avoidance

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Abstract

This paper reviews improved operational concepts for collision avoidance, addressing the challenges that electric propulsion introduce in Collision Avoidance operations, including during early and final phases of the satellite lifetime (orbit raising and end-of-life operations) as well as during routine operations already in the target orbit. First, those challenges are detailed, outlining how it impacts collision avoidance procedures, of which thruster uncertainty plays a dominant role due to its rapid accumulation during expected long-duration manoeuvres performed with electric propulsion systems (required to reach the desired delta-V). If the uncertainty accumulation is not addressed, conjunction events may appear in the dilution of probability region, where knowledge of the primary and secondary is too poor to take mitigation action. This situation therefore should be avoided as much as possible. The design of a collision avoidance manoeuvre becomes increasingly complex for low-thrust propulsion systems, where the thrust profile needs to be optimized throughout the duration of the manoeuvre. SpaceX's Starlink satellites along with the OneWeb constellation are a clear representation of the widespread use of low-thrust propulsion. Hence, the deployment of thousands of electric propulsion satellites fosters the development and introduction of new approaches to collision avoidance design and operations. An analysis of derived improved operational concepts are then detailed in this paper, focusing on improving the conjunction screening and collision avoidance manoeuvre operational concepts, explaining what area of collision avoidance (screening, mitigation) each concept improves, by how much (e.g. uncertainty reduction, CAM decision delay and mission impact), and what operational scenarios such concepts are applicable to (electric orbit raising, GEO station keeping manoeuvres etc.). The paper ends by presenting the results of a set of simulations carried out assessing the impact of improved operational concepts for different scenarios, compared against a baseline nominal operational concept, which is currently used in operations by satellite operators.

Keywords: SSA, collision avoidance, space debris, electric propulsion, operational concepts, collision avoidance manoeuvre, conjunction screening

Acronyms/Abbreviations

ACPL	Accepted Collision Probability Level	ISL	Inter-Satellite Link
CA	Collision Avoidance	OCM	Orbital Control Manoeuvre
CAM	Collision Avoidance Manoeuvre	OD	Orbit Determination
CDM	Conjunction Data Message	PoC	Probability of Collision
CREAM	Collision Risk Estimation and Automated Mitigation	SKM	Station Keeping Manoeuvre
		SLR	Satellite Laser Ranging
DOI	Depth of Intrusion	SMA	Semi-Major Axis
dV	Delta-V	SSA	Space Situational Awareness
EOR	Electric Orbit Raising	STM	Space Traffic Management
EOL	Electric Orbit Lowering/End Of Life	SST	Space Surveillance and Tracking
EP	Electric Propulsion	TCA	Time of Closest Approach
GNSS	Global Navigation Satellite Systems	TLE	Two Line Elements

1. Introduction

The number of orbiting objects is increasing at an ever-growing pace, inevitably driving up the number of conjunction events. This is forcing the Space Traffic Management (STM) industry to expand the proportion of automated tasks within their conjunction detection and avoidance practices. During normal operations, possible conjunctions are identified, tracked and, if necessary, a manoeuvre plan is created to avoid them. This brings the need to define not only efficient Collision Avoidance Manoeuvre (CAM) design algorithms, but also robust operational concepts for missions using chemical or electric propulsion for collision avoidance purposes.

Operational concepts for collision avoidance are defined by different aspects, like location (on-ground vs. on-board) of each of the Collision Avoidance (CA) related processes (CA screening, CAM design, CAM decision), required interaction and flows of information (orbits, potential collisions, etc.) among different stakeholders (satellite, satellite operator, CA service provider), delays in the communications due to operational overheads (human or geometry related). All of these aspects together define the possible operational timeline associated with the CA operations. The nominal operational concepts used in CA by space agencies (ESA, NASA, DLR, JAXA, and CSA) are analysed in [1] and a generic approach is identified in that reference. It shows that while some CA processes discussed above are combined or expanded, the work carried out is consistent.

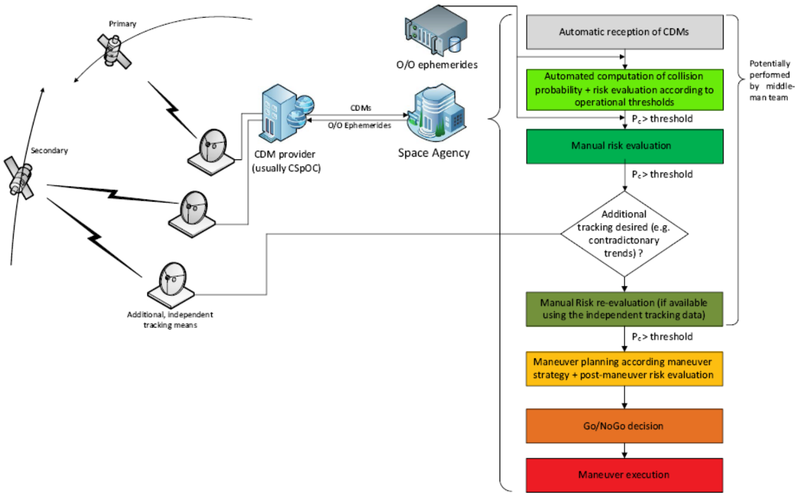

Figure 1: Conjunction assessment generic approach [1].

1.1 Challenges of Electric Propulsion on CA

Given the very low thrusting force provided by electric propulsion, the reactivity of the satellite is considerably reduced making it impossible to wait until the last few orbits to perform the collision avoidance manoeuvre. The MICROSCOPE satellite for example represents an extreme case as it is equipped with cold-gas thrusters for attitude control and hence required a 12 hr low-thrust manoeuvre to change its semi-major axis (SMA) by 100m [2]. This forces satellite operators to take the go/no-go CAM decisions earlier in time compared to traditional chemical thrusters, and execute the low-thrust CAM with sufficient lead time. Thus, decisions are taken with higher uncertainty on the actual risk of the event and the orbit of the chaser object, and this brings as well the risk of a higher amount of false positives (where no mitigation action would be needed).

There is a trade-off with respect to the time of the manoeuvre decision and execution: the longer the wait, the more fuel consumption is required to reach the desired delta-V (dV) before time of closest approach (TCA). Taking advantage of automation of operational concepts and procedures (either on-ground, on-board or a combination of the two) may assist in mitigating the reactivity challenges faced with electric propulsion (EP). In this regard, the most prominent example would be the Starlink satellites where go/no-go CAM decision is taken on board of the satellite, based on the orbital information of the primary satellite available on-board (estimation and prediction from GNSS receiver and AOCS software) and the orbital information of secondary objects provided by CA service providers via conjunction data messages (CDMs) to satellite operators.

Analysis of [3,4,5,6,7] helped determine electrical thruster errors range from 0.1% to 5% in the thrust module, with the most typical value being 1%, and typical pointing errors range from 0.5 to 5º. It was identified that uniform errors in the thrust module had greatest impact on the orbital accuracy, which could be one or several orders of magnitude larger than any other manoeuvre error. If frequent or long-duration manoeuvres are required, these errors accumulate uncertainty at a rapid pace, especially if no effort to mitigate them is in place in the CA operational timeline. An example of requiring frequent manoeuvres includes the low-thrust manoeuvre strategy for orbital control manoeuvres (OCM). LEO OCMs are typically executed daily, or weekly (depending on the mission and operational constraints) compared to OCMs with chemical propulsion being quarterly/monthly (in-plane manoeuvres) or yearly (out-of-plane manoeuvres).

The electric orbit raising (EOR) and lowering (EOL) phases are particularly challenging in terms of CA for satellites whose only propulsion system is based on electric propulsion thruster. In such phases the satellite is thrusting almost continuously. The thruster performance can vary which is very difficult to be captured in orbit determination (OD) and propagation of the primary. Initial analysis determined that thrusting errors can reach hundreds of kilometres when continuously thrusting over several days. It is often stated that the best approach after deciding to mitigate during EOR/EOL, in case of a collision, is to stop thrusting until the TCA [8]. Here, the thrust is interrupted or significantly reduced at specific points along the orbit to achieve a separation between the involved objects. However, depending on the geometry of the conjunction this approach might be inefficient. This phenomenon is especially critical for near head-on collisions where a high radial separation is necessary and this cannot easily be obtained through switch-offs of the thruster, which is acting mainly in the along-track direction during those mission phases.

With frequent or continuous manoeuvres, the uncertainty can accumulate at a rapid pace, to the point that the thruster uncertainty of the primary becomes the dominating source, surpassing that of the secondary object (which is most typical for nominal conjunction events). Furthermore, if the uncertainty is large enough at TCA, it is possible that risky conjunction events go undetected: the uncertainty exceeds the threshold limits of the conjunction screening analysis. This is undesirable as a much larger screening volume is needed in the screening analysis, therefore an additional computational cost is imposed in those analysis. Similarly, and also related to the degree of uncertainty, especially where low-thrust devices are continuously thrusting (thus uncertainties are large), there exists the problem of dilution of probability [10] where collision probabilities computed may be insignificant, not because the risk is small but because the level of knowledge of the objects' orbits involved in the conjunction is very low. These types of situations need to be avoided and mitigated, as conjunctions under dilution of probability are not actionable (i.e., cannot be mitigated).

Operational constraints are associated with the use of EP devices, for instance the impact of eclipses (when batteries cannot be charged), or the responsiveness of the propulsion system to perform several consecutive manoeuvres as a consequence of the depth of discharge of the batteries or the fuel tanks. Due to the long time required for performing low-thrust manoeuvres, subsystem units might be exposed to sunlight for a long duration which increases the thermal stress of these subsystems. This can also impose a limit on the maximum duration of the manoeuvre. Additional thruster limitations such as the minimum and maximum thrusting time can impact how long a manoeuvre can last, whereby considerations of viability and mission impact must be addressed. Other constraints may come from the platform, such as exclusion areas for sensors onboard the satellite or the maximum slew rates allowed by the AOCS.

These challenges justify the need for more complex CAM design approaches, where the thrust profile must be optimised throughout the duration of the manoeuvre, while ensuring there are no violations of operational constraints. Moreover, with an increasingly congested space environment, it is also necessary to account for multiple conjunction events when designing the CAM. This allows, on the one hand, to simultaneously mitigate multiple high-risk events and, on the other hand, to prevent new ones appearing as a consequence of the CAM. This approach is of increasing interest with the recent deployment of mega-constellations.

Based on these challenges introduced by low-thrust propulsion systems it warrants the need to analyse their impacts on collision avoidance and CAM design. This paper therefore presents effective operational concepts for collision avoidance involving satellites with electric propulsion systems, including designing advanced CAM strategies.

2. Operational Concepts Analysis

While analysing the impacts EP have on the Operational Concepts, improvements to the typical approach to CA were identified, falling into one of two categories: conjunction screening or collision avoidance. Tables 1 and 2 correspond to a subset of the derived operational concepts, for the two categories respectively. Scenarios applicable for each concept have been stated, for which Appendices A provides a table describing each of them.

2.1 Operational Concepts for Conjunction Screening

The following derived operational concepts for conjunction screening focus on the primary challenges to EP systems: uncertainty reduction, timeliness improvements and risk analysis.

Table 1: Proposed improved operational concepts for conjunction screening. The process locations are: G = ground; S = on board and H = hybrid. The uncertainty reduction, timeliness improvement and risk analysis values are: L = low; M = medium and H = high.

Concept ID	Operational Concept	Process Location	Applicable Scenario(s)	Uncertainty Reduction	Timeliness Improvement	Risk Analysis
MA4	Frequent calibration of thruster performances	G,H	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, MG1, MG2, ML3	M	N/A	N/A
MA5	Feedback control (GNSS measurements).	S	RL1, RL2, RG1, RM1, LL1, LL2, ML1, ML2, ML3, ML4, ML5, ML6	H	H	N/A
MA6	Feedback control (High-precision accelerometer)	S	RL1, RL2, RG1, RM1, LL1, LL2	H	N/A	N/A
OD1	The use of more precise data to reduce the initial uncertainties	G,H,S	ML2, ML4, ML5, ML6	L	N/A	N/A
OD2	Receive support from space surveillance sensor networks (e.g. telescopes, SLR, SST radar)	G,H	RG1, RM1, RG2, MG1, MG2, MM1	L	M	N/A

Frequent calibration of the thruster performance with available measurements, MA4, (accelerometers, or GNSS measurements) aims to increase the accuracy of the predicted manoeuvre, therefore reduce (or prevent growing) orbital uncertainties. [10] and [11] used frequent thruster calibration of their electric propulsion systems to minimise thruster uncertainty. Initial analysis showed that small thrust errors of 1% can cause along-track position uncertainty that can reach 10km in just 2 days. This concept is useful for all scenarios with frequent manoeuvres but has the largest impact on long-thrusting manoeuvres scenarios such as the EOR/EOL. This concept does however require frequent, precise and recent tracking data, which may not always be available.

Including a feedback control loop using GNSS receivers (MA5) or accelerometers (MA6), allows for more CA operations on-board, therefore more automation, as the satellite can auto-correct its predefined flight path with on-board orbit determination through accurate and almost continuous updates. With this concept it is ideal that the EP system has the ability of fast and fine thrust module and orientation corrections (which is typically the case), to utilise this concept to its fullest capacity. Concept MA6 would suit missions with no GNSS data available (lack of receiver or signal), utilised in the GOCE mission [12]. Accelerations in EP satellites are typically 0.01-0.1mm/s^2, from which the accelerometer could detect deviations < 0.1% of the nominal thrust. However, a deviation with respect to the reference trajectory will be unavoidable because of the accumulated undetected errors in the acceleration, but can be compensated afterwards ensuring the satellite stays around its predefined flight path with certain margins (i.e. space corridor). These concepts would suit satellites in LEO, with a high level of autonomy capability, and MA6 would also require high accuracy orbit prediction, to avoid deviations from the reference trajectory the accelerometer uses. Concept MA5's effectiveness would decrease for other regimes due to reduced

GNSS signal availability for precision pointing, however it can improve the timeliness, since if the spacecraft is equipped with a GNSS receiver, it can have very frequent updates on its state vector. A combination of both concepts could balance each of their flaws. Both concepts would have the most impact in long thrusting phases (EOR/EOL), allowing for reductions in the large uncertainties expected. This operational concept can be applied to both the initial manoeuvre plan a satellite has, or for a CAM if it is needed, of which the latter case is expanded on in section 2.2.

By using more precise data (concept OD1), e.g. with GNSS receivers or retroreflectors, where the latter are used for satellite laser ranging (SLR) measurements (accuracy of a few metres can be achieved for uncooperative targets, this is, without laser retroreflector on board), the initial uncertainties of the state vector can be reduced, and if there are no manoeuvres planned the uncertainty of the estimated orbit can also be reduced. Also, as mentioned, if the satellite has a GNSS receiver, the timeliness is considerably improved. Support from sensor networks such as telescopes (concept OD2) during specific phases of the mission (e.g. post manoeuvres for manoeuvre calibration, during EOL transfer, etc) can be useful to obtain more precise orbital estimates in a shorter timeline, especially if the aforementioned on-board instruments are not available. These operational concepts depend on whether there are new observation data available.

Further considerations of minimising the uncertainty growth, instead of reducing, were also explored. It is proposed to cut-off the low-thrust propulsion engine once uncertainties reach a threshold (e.g. a fraction of the screening volume), until its state is better determined. If the uncertainty is allowed to freely grow, the knowledge of the conjunction (particularly the primary) will be too poor to act on i.e. it has entered the depth of intrusion (DOI).

2.2 Operational Concepts for Collision Avoidance

The operational concepts derived for collision avoidance related aspects of the CA procedures have been graded in terms of the mitigations of the main challenges of EP systems that impact conjunction screening: delay in the CAM decision time, reduce mission impact, reduce the operational workload, and to increase robustness. Postponing the decision of the CAM is done to minimise the number of false positives, as more accurate data is available. The impact of CA operations can be measured by, at least, the fuel consumption, operational lifetime, mission duration and out-of-service time. Automation is paramount in reducing operational workload to avoid time lost during human intervention. Increasing robustness results from better modelling the execution of low-thrust propulsion, particularly thruster pointing and magnitude errors, to avoid unrealistic risks when computing the probability of collision (PoC).

All derived operational concepts in Table 2 share a commonality of aiming to reduce the CAM delay, which is much more apparent in low-thrust manoeuvres due to very small thruster accelerations. Being able to decide later grants the operator extra time to wait for more accurate data, risk analysis and CAM design. It may even be the case that with more accurate data, the conjunction no longer requires action (reducing the number of false positives during risk assessment). Utilisation of inter-satellite links (ISL) or GNSS networks with their receivers (concept CD1) could mitigate points of no-visibility periods, therefore allowing to decide whether to perform a CAM later. The use of ISL can allow postponing the CAM decision time up to almost 12 hrs in the case of Sun-Synchronous orbits, where ground passes can happen once every half Earth rotation, that is, if only one station is available.

Scenarios with constant visibility such as GEO are suitable for the optimal 3D CAMs operational concept executed very close to TCA (CD2), as CAM computation will be carried out with the most updated information, therefore reducing uncertainties at TCA. This may allow postponing the decision until 3-6 hrs before TCA instead of 12 hrs in the typical approach. In other regimes this can also be beneficial, such as in MEO and GTO where the orbital periods are still large, the decision could be postponed from 6-9 hrs to 2-3 hrs before the TCA. However, this greatly depends on the SMA, since the orbital periods in these regimes can range from 2 hrs to almost 24 hrs. The process could be done on board, if enough computational power is available. The ability to manoeuvre in 3D offers a wider time range, where an optimal CAM can deviate from the common CAM design strategy used in current CA operations: an along-track manoeuvre to either increase radial or along-track separation.

Table 2: Proposed improved operational concepts for collision avoidance. The process locations are: G = ground; S = on board and H = hybrid. The CAM delay, mission impact reductions, operational workload reduction and robustness increase values are: L = low; M = medium and H = high.

Concept ID	Operational Concept	Process Location	Applicable Scenario(s)	CAM Delay	Mission Impact Reduction	Operational Workload Reduction	Robustness Increase
CD1	Late telecommand paths to postpone the decision time	G,H	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, ML2, MG1, MG2, ML3, ML4, ML5, ML6	H	L	L	L
CD2	CAM closer than one semi-period before TCA to postpone the CAM decision time	G,H	MG1, MG2	H	M	L	L
OW1	CAM design on-board	S	RL1, RL2, RG1	H	L	H	M
OW2	CAM design on-ground and CAM decision on-board (from pre-loaded CAM)	H	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, ML2, ML3, ML4, ML5, ML6	M	L	H	M
MI5	Shut-down engine during EOR/EOL	G,H,S	RL1, RL2, RG1, RM1, LL1, LL2, RG2	L	H	M	M
MI6	Modify planned manoeuvres in EOR/EOL or SK	G,H	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, MG1, MG2, ML3	L	H	M	L
IR1	Model the uncertainty of the CAM	G,H,S	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, ML2, MG1, MG2, ML3, ML4, ML5, ML6	L	L	L	H
IR2	Reduce the CAM uncertainty (ref. feedback control)	S	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, ML2, MG1, MG2, ML3, ML4, ML5, ML6	L	M	L	H
IR4	Consider multiple events in the CAM design	G,H,S	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, ML2, MG1, MG2, ML3, ML4, ML5, ML6	L	M	M	H
IR5	Use multiple metrics for the post-CAM thresholds	G,H,S	RL1, RL2, RG1, RM1, LL1, LL2, RG2, ML1, MG1, MG2, ML3	L	L	L	H

If a satellite has precise measurement instruments on board, such as GNSS receivers or accelerometers, then accurate and frequent OD is available, and on-board CAM design concepts (OW1 and OW2) are viable options. Being independent from ground passes for OD information, the satellite can choose to delay the CAM decision time (concept OW1), therefore saving a large amount of resources. An example is the Starlink constellation, where 2219 CAMs (using a PoC threshold of 10^{-5}) have been performed autonomously through on-board CAM capabilities in approximately 6 months [13]. The major limiting factor is what processing power the satellite has. If it lacks the power for on-board CAM design, the fully on-board concept can be adjusted to a hybrid approach, where the CAM design is computed on-ground and uplinked to the satellite, where it can take advantage of more recent (therefore accurate) OD to re-assess the risk and take the decision on-board (concept OW2). While the optimal CAM may become sub-optimal based on the latest data, possible mitigations can be set where the satellite can adapt the initial CAM through more simplified approaches, within the limits of its processing power constraint. Furthermore, while the CAM procedures are done on-board, this concept will still require ground coverage to receive the CDMs for screening, with the associated bandwidth requirements. With a high dependency on GNSS receivers, this concept will be most suitable for LEO orbital regimes.

Modifying a manoeuvre plan to mitigate the conjunction risk (concept MI6) can be achieved if the manoeuvre plan is to be executed before the conjunction TCA. This is particularly useful in GEO satellites using electric propulsion, where station keeping manoeuvres (SKMs) occur every 12-24 hrs and there is usually some margin to modify the existing plan. Within this approach there are several options: delay a manoeuvre, advance a manoeuvre, recombine manoeuvres (skip a SKM, then the missed dV is included in the next planned SKM), or change the manoeuvre orientation. Manoeuvre recombination may not be viable for all missions as it depends on the thrusting capability of the engine to provide the additional dV, which could be twice as large as nominal ones. While additional dV is incurred with this concept, it is often very low, and it avoids the need for an additional CAM for conjunction mitigation. For application of this operational concept for EOR/EOL phases, utilisation of concept MI5 is recommended, as stated earlier, where thruster shutdown(s) act as a manoeuvre plan modification, and the EOR/EOL phase then includes coasting arc(s) for collision avoidance. This allows to mitigate the collision risk because of two main factors: the first one is that by shutting down the thrusters, the nominal trajectory is modified, hence changing the conjunction geometry and risk. The second one is that since EP is the main source of uncertainties, by shutting it down the uncertainties of the state vectors at the TCA are reduced. The main disadvantage of this approach is the mission impact that this may have, since the orbital transfer time is increased. However, these shutdown intervals (coasting arcs) are typically very short compared to the overall thruster actuation time interval, so its negative effect might easily be compensated in following operational cycles at little extra dV cost.

With thruster uncertainty being a dominant challenge in developing new operational concepts, the ability to model such thruster errors and account for its covariance increase must be considered (IR1). An extension on Gates Method [14] for low-thrust, non-linear methods is recommended. If ignored, the post-CAM analysis will not be a realistic representation of the mitigation action. If the uncertainty of the CAM is accounted for, then the question arises of how to reduce such uncertainties. In the case of CAMs with EP large uncertainties due to the thrust are one of the key problems. Hence, mitigating this uncertainty is of great interest. Employing those concepts previously analysed for reducing the uncertainty (concepts MA4, MA5, MA6, with concept IR2) go hand-in-hand with modelling the thruster uncertainty during CAM design. If this is combined with other concepts such as on-board CAM design (OW1) or decision (OW2), it can give the satellite a high level of autonomy at the same time that it is ensured that the uncertainties are kept bounded. Further automation introduces additional benefits as it also reduces human interaction delays, improving the overall timeliness of the conjunction analysis and reduces CAM timeline constraints for low-thrust propelled satellites. The main application of this concept would be in the LEO regime, given that it could also benefit from the combination of several concepts that employ GNSS data. The application of this concept extends to every orbit maintenance scenario regardless of the orbital regime (except if only GNSS receivers are being used, then GEO may not be viable) since the main requirement is high-precision measurements from the aforementioned instruments and the satellite’s capacity to correct its own thrusting error.

In recent years, it has become increasingly frequent that a single satellite is involved in several high-risk events at or around the same time. In addition, the increasingly congested space environment increases the possibility of a CAM leading to a new high-risk event (determined in the post-CAM analysis). The ability to design a CAM that considers multiple conjunctions at the same time could be utilised to avoid executing multiple CAMs sequentially (concept IR4). This has been analysed and presented in [15], using a robust multi-objective CAM optimiser based on numerical methods with the ability to set a global PoC constraint that accumulates the PoC for each high-risk event. Even though it often requires more computational effort (with the use of a robust optimiser), and a deeper analysis, it allows for saving fuel and operational workload since one manoeuvre mitigate multiple events, as opposed to the traditional approach of one manoeuvre (or multiple) per event. In addition, it prevents the CAM from causing additional high-risk events. This concept offers the most benefit to the LEO orbital regime as it is most congested, however it could be applied to the other orbital regimes as well as any orbit maintenance scenario. This includes EOR/EOL scenarios, although to a lesser extent due to significant uncertainties and longer propagation times expected to mitigate the conjunction of multiple secondaries against a primary satellite in a CAM design.

As stated previously, the large covariances associated with low-thrust manoeuvres is dominant for EP systems, therefore accounting for them through advanced risk assessment methods is recommended, for which the commonly used risk metrics (miss distance, radial miss distance and PoC) do not give a clear image of the true risk of a conjunction and more advanced metrics are recommended (concept IR5). The Scaled PoC decision metric considers the geometry, uncertainty and size of the objects, and is able to determine more realistic uncertainty estimations (compared to PoC) through considering the accuracy of the uncertainties. The Mahalanobis distance is another metric to consider as it is able to detect if a conjunction is within the dilution of probability (when the Mahalanobis distance < 1). Finally, it is known that typically the evolution of a conjunction event makes the covariance decrease as it gets closer to the TCA. This leads in most cases to a reduction in the PoC, hence, the collision risk. In order to avoid false positives, a threshold can be established in the time to TCA to avoid rising conjunction alerts if there is still plenty of time until the TCA. This provides the opportunity to wait for more updates. A combination of the advanced risk metrics increases the robustness of the risk assessment, whereby metric thresholds can applied during the CAM design to avoid manoeuvre uncertainties from growing too large. These metrics can be used in every scenario, separately or combined, since they are independent of the orbital regime and operational mission, however, different metrics will be more or less useful in different situations. It is therefore most suitable to decide which metric(s) to consider on a case-by-case basis.

3. Simulation Approach

The following bullets describe the simulation environment, designed to test nominal (concepts commonly used) and improved operational concepts for conjunction screening and collision avoidance:

- A reference set of conjunctions are generated based on the reference ephemeris (a single ephemeris, covering one day) of the primary object (e.g. undergoing EOR, GEO Graveyard EOR…) and screened against successive TLE catalogues for different days (different catalogues, but referenced to the day of the reference ephemeris). A large set with statistical significance is built this way.
- Analysis of JSpOC CDMs, using data from ESA missions, is used to generate covariance abacuses for the secondary object, depicting its evolution depending on the orbital parameters and time to TCA.
- The reference ephemeris and predicted ephemeris for the primary are used differently. The reference ephemeris is used for the conjunction screening, which corresponds to the flown trajectory, and is therefore unknown during the screening and planning phase in an operational environment. The predicted ephemeris is used to re-analyse the reference set of conjunctions. This way, one can evaluate how well the truly encountered conjunctions are detected and assessed by means of the nominal and the improved operational concepts. The predicted ephemeris are generated in a Monte Carlo fashion by perturbing the reference ephemeris. The perturbation (for each sample) is drawn from a given sigma level, according to which the primary's covariance.
- To generate a realistic evolution of the primary's covariance (required for the previous step), an error model to describe the thruster's uncertainty is required. To that end, a time-correlated error model is implemented, with configurable time scales for errors in pointing and thrust modulus.

For each scenario and operational concept, the conjunction analysis is performed in two different instants in the CA timeline: at the critical update (where the operator is required to take a decision to manoeuvre), and the last update before TCA. The latter allows to extract extra information such as the rate of false positives and negatives: whenever an event is characterised as ALERT in one of the conjunction updates before the decision time, but not in the last one.

The same robust multi-objective CAM optimiser using numerical methods in [15] was used for the low-thrust CAM design and optimisation for each scenario. The CAM design criteria depends on the operational concept.

4. Operational concepts to be simulated

Table 3 details the scenarios with each of the improved operational concepts simulated. These focus on EOR/EOL mission phases as this is where uncertainties are largest as a result of continuous thrusting. The last column indicates the translation of the operational concept to the simulation environment. Please note, that while scenario RG1 is being simulated twice, they are covering different stages of the GTO-to-GEO transfer: GTO-to-GEO EOR (Interval 1) is the initial stage, while GEO insertion is the final stage (including entering its GEO slot).

Table 3: Improved operational concepts for conjunction screening and CAM for each scenario to simulate.

Scenario	Operational Concept Category	Improved Operational Concepts Used	Simulation Definition
LEO-to-LEO EOR Low (RL1)	Screening	**MA5:** Feedback control (GNSS measurements)	The covariance of the primary is considered fixed along time 100x10x10 [m] in the TNW reference frame
	CAM	**MI5:** Shut-down engine during EOR/EOL to avoid extra fuel consumption **OW1:** CAM design on-board	The minimum shutdown is based on the latest information
GTO-to-GEO EOR (RG1) INT1	Screening	**MA5 & MA6:** Feedback control (high-precision accelerometer + GNSS measurements)	The covariance of the primary is considered fixed along time 100x10x10 in the TNW reference frame, in the perigee. After each revolution, the covariance grows with the accelerometer errors
	CAM	**MI5:** Shut-down engine during EOR/EOL **OW1:** CAM design on-board	The minimum shutdown is based on the latest information
GEO Insertion EOR (RG1)	Screening	**MA6:** Feedback control (accelerometer measurements)	Manoeuvre error based on accelerometer errors
	CAM	**MI5:** Shut-down engine during EOR/EOL	The minimum shutdown is based on the latest information
GEO Graveyard EOR (RG2)	Screening	**MA6:** Feedback control (accelerometer measurements) **OD2:** Receive support from space surveillance sensor networks (e.g. telescopes, SLR, SST radar)	Manoeuvre error based on accelerometer errors Ephemeris from primary based on ranging + telescopes observations
	CAM	**MI5:** Shut-down engine during EOR/EOL	The minimum shutdown is based on the latest information

In terms of the primary's predicted ephemeris, Table 4 details the time of the most recent OD (before the day of analysis), for the nominal and improved operational concept, and the configuration of the error model for the thruster uncertainty. For the nominal operational concept, a correlated time scale, both for the modulus and for the pointing errors, equal to one orbital period is assumed. In contrast to this, the improved operational concept makes use of GNSS measurements which either allows to maintain a constant covariance (e.g. LEO-to-LEO EOR Low) or to correct thruster errors in between consecutive timesteps, leading to a null time scale.

Table 4: Time of the most recent OD before the day of simulations and thruster error model configuration.

Scenario	Operational Concept Type	Decision Time to TCA (hrs)	Thrust Error Model		
			Modulus (%)	Pointing (deg)	Time Scale (Orbital Periods)
LEO-to-LEO EOR Low (RL1)	NOMINAL	12	1	0.5	1
	IMPROVED	1	-	-	-
GTO-to-GEO EOR (RG1) INT1	NOMINAL	36	1	0.5	1
	IMPROVED	7	1	0.5	0
GEO Insertion EOR (RG1)	NOMINAL	36	1	0.5	1
	IMPROVED	13	1	0.5	0
GEO Graveyard EOR (RG2)	NOMINAL	36	1	0.5	1
	IMPROVED	13	1	0.5	0

To provide an example of all this logic, considering the GTO-to-GEO EOR INT1 scenario, the predicted ephemeris for the primary object with improved operational concepts applied takes advantage of both GNSS coverage during perigee passage, and accelerometers to mitigate uncertainty growth during the rest of the orbit. This way, when comparing a sample predicted ephemeris of both nominal and improved operational concepts, with respect to the target reference ephemeris, the orbital differences are determined. For two particular samples, the maximum differences in the predicted ephemeris decreases from 60km to 3 km, as can be seen in figure 2.

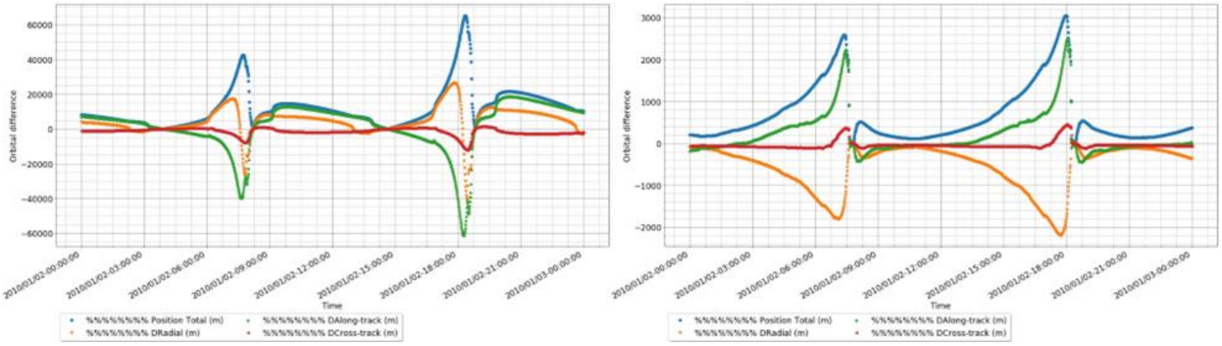

Figure 2: Sample trajectory for the GTO-to-GEO EOR INT1 scenario under the nominal (left) and improved (right) operational concept conditions.

5. Results and Discussion

The output of the conjunction screening is a set of processed CDMs indicating:

- A re-assessment of the event incorporating covariance information for the secondary according to the constructed abacuses, state and covariance information for the primary, derived from the predicted ephemeris (alternatively to the reference ephemeris, which is the one used to generate the reference conjunctions), for each of the reference conjunctions.
- From the set of re-assessed conjunctions, the annual manoeuvring rate required to mitigate all conjunctions above a given Accepted Collision Probability Level (ACPL) can be determined. As the ACPL is decreased (e.g. from 10^{-3} to 10^{-7}), the overall risk reduction and residual risk can be evaluated. For instance, if all the conjunctions for a given scenario would lie in the range 10^{-5} to 10^{-4}, selecting an ACPL of 10^{-3} would not declare any event as ALERT, while an ACPL of 10^{-7} would require all conjunctions to be mitigated, achieving a residual risk of 0 and a risk reduction of 1 (normalised).
- By comparing the processed CDMs between the critical and the last updates, the rate of false positives and false negatives can also be evaluated. Notice however, that their definition is somewhat ambiguous. In a real environment, virtually all events would correspond with false positives (for an ACPL of 10^{-4}, it is expected that there will be 9,999 false positives out of 10,000 events).

These outputs are passed onto the CAM design module to extract annual dV figures required to mitigate different ACPL targets, as well as the rate of successful event mitigation.

5.1 LEO-to-LEO EOR Low Scenario

The improved operational concept applied for this scenario involves a fixed covariance matrix of 100x10x10m in the TNW frame, associated to GNSS measurements, in contrast to the nominal operational concept where the uncertainty of the thruster is allowed to grow according to the configuration of the error model in Table 4. The introduction of the improved operational concept results in a decrease in the required annual manoeuvring rate across all ACPLs. Consequently, the crossing of the residual and reduced risk is also anticipated, by approximately half an ACPL unit. Similar conclusions can be reached when considering depth of intrusion as a threshold to trigger a CAM.

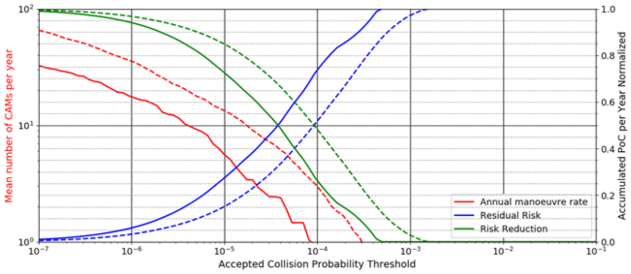

Figure 3: Mean number of CAMs, normalised residual risk and risk reduction depending on the ACPL for LEO-to-LEO EOR low scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

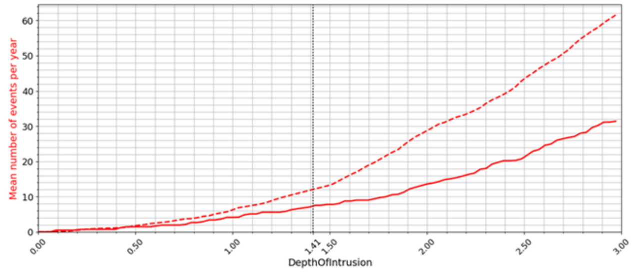

Figure 4: Cumulative histogram of the number of events per year depending on the Depth of Intrusion (Mahalanobis distance) for LEO-to-LEO EOR low scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

While the improved operational concept does in fact suggest that less manoeuvres are required overall, the improvement is not by orders of magnitude. However, one shall consider that both the nominal and the improved operational concepts analyse the same reference conjunctions, and although the TCA is recomputed in the conjunction analysis step, the difference of the predicted and flown ephemeris is greater under nominal considerations. This is in spite of the fact that the covariance management is much poorer, the miss distance is also expected to be larger, which may prevent the event from entering into dilution of probability region.

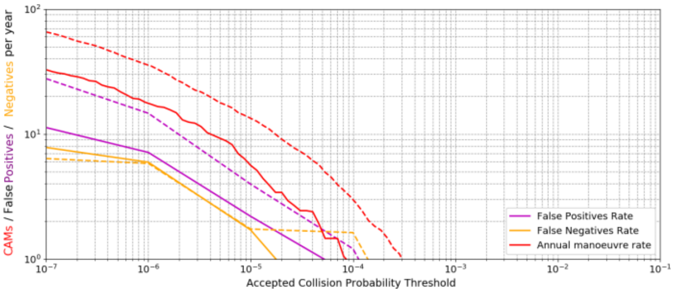

Figure 5: False positives, false negatives, and CAMs per year for LEO-to-LEO EOR low scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

Figure 5 indicates that the false positive rate does represent a large amount of the required manoeuvres, although it is not close to representing them in total. On the other hand, the consideration of an improved operational concept is seen to barely affect the false negatives rate.

Concerning CAM computation, figure 6 displays a dV curve which mimics the evolution of the annual manoeuvring rate, with dV per manoeuvre of around 100 mm/s when the most restrictive ACPL of 10^{-7} is selected, and only of around 10 mm/s when a typical ACPL of around 10^{-5} is chosen. Figure 7 indicates that while the software runs successfully for almost every execution, it is not possible to mitigate all conjunctions. This is especially the case for the lower ACPL values (for a conjunction event with an initial PoC of 10^{-4}). For these ACPLs, it is easier to mitigate down to an ACPL of 10^{-5} than it is to 10^{-7}, as the latter require higher dVs. Additionally, the tighter schedule associated with the improved operational concept implies that a lower number of conjunctions are mitigated. This can be easily overcome by selecting extended time horizons.

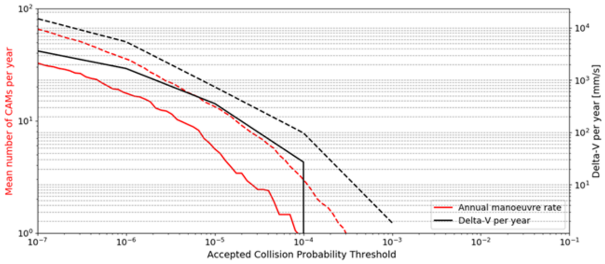

Figure 6: Mean number of CAMs per year and dV used depending on the ACPL for the LEO-to-LEO EOR Low scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

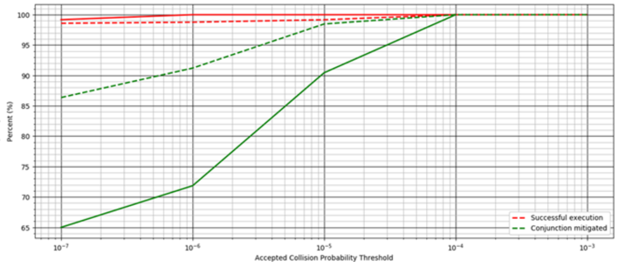

Figure 7: Successful software execution and conjunction mitigation rate depending on the ACPL for the LEO-to-LEO EOR Low scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

5.2 GTO-to-GEO (Interval 1) Scenario

The improved operational concept applied for this scenario involves GNSS coverage for improved tracking, maintaining a constant covariance near perigee passage, and the use of on-board accelerometers which allow to reduce the uncertainty derived from thrusters operation for the rest of the orbit. This is in contrast to the nominal operational concept in which the uncertainty of the thruster is allowed to grow according to configuration of the error model in Table 4. Figures 8 and 9 reveal a significant reduction in the annual manoeuvre rate, especially for lower ACPL values of around one order of magnitude. This follows from an improved conjunction assessment, as can also be derived from the DOI criteria in figure 9.

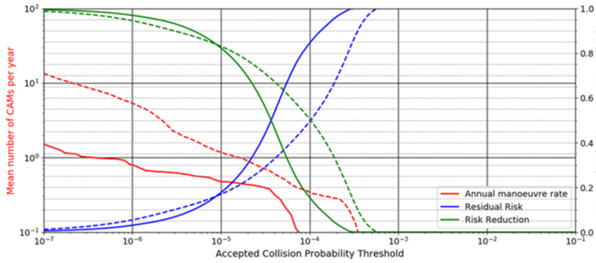

Figure 8: Mean number of CAMs, normalised residual risk and risk reduction depending on the ACPL for GTO-to-GEO (int. 1) scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

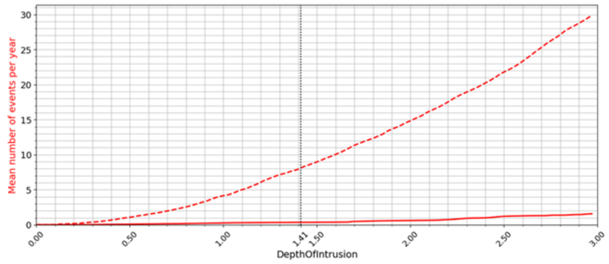

Figure 9: Cumulative histogram of the number of events per year depending on the Depth of Intrusion (Mahalanobis distance) for GTO-to-GEO (int. 1) scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

Additionally, when considering the improved operational concepts, the false positives rate is seen to almost match the annual manoeuvring rate, and produces a significant reduction in the rate of false negatives.

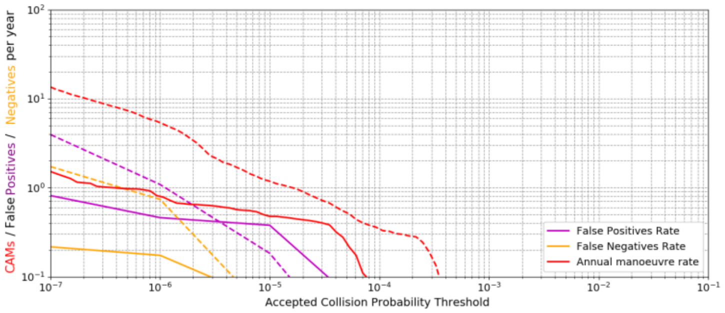

Figure 10: False positives, false negatives, and CAMs per year for GTO-to-GEO (int. 1) scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

In terms of dV expenditure and successful mitigation, figures 11 and 12 reveal consumptions of around 100 mm/s per manoeuvre across all ACPLs and mitigation rates above 90%. This number, although significant, is consistent with the onboard acceleration level, which is much larger than those in other scenarios, such as the LEO-to-LEO EOR Low transfer.

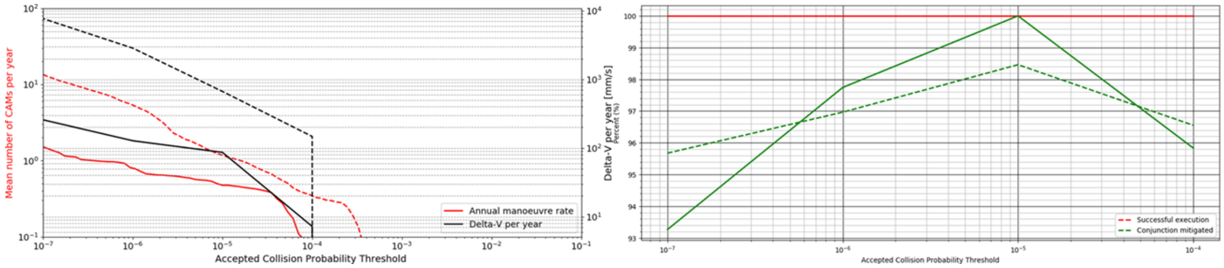

Figure 11: Mean number of CAMs per year and dV used depending on the ACPL for the GTO-to-GEO (int. 1) scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

Figure 12: Successful software execution and conjunction mitigation rate depending on the ACPL for the GTO-to-GEO (int. 1) scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

5.3 *GEO Insertion EOR Scenario*

The improved operational concept applied for this scenario involves on-board accelerometers which allow to reduce the uncertainty derived from thrusters operation, in contrast with the nominal operational concept in which the uncertainty of the thruster is allowed to grow according to configuration of the error model in Table 4. Contrary to the GEO Graveyard EOR scenario (discussed in section 5.4), conjunctions are encountered near the end of the transfer, when the object crosses the GEO ring, to insert the satellite into its allocated slot. This implies that the uncertainty of the system when performing the risk assessment is at its maximum.

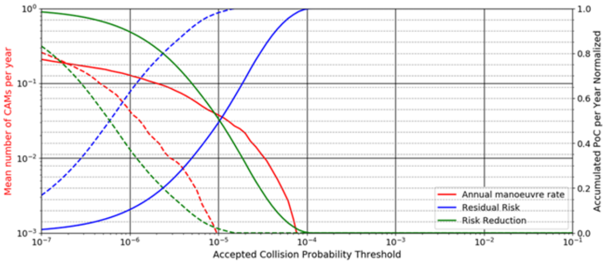

Figure 13: Mean number of CAMs, normalised residual risk and risk reduction depending on the ACPL for GEO Insertion scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

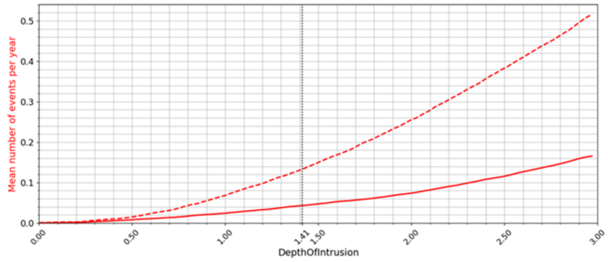

Figure 14: Cumulative histogram of the number of events per year depending on the Depth of Intrusion (Mahalanobis distance) for GEO Insertion scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

Figure 13 indicates that a large number of events are detected by means of the improved operational concept in higher ACPL ranges. This implies that the risk assessment under improved operational concept considerations attributes to a higher risk to events that the nominal operational concept would not raise an ALERT. This is consistent with the argument presented above. The larger uncertainty in the problem when applying the nominal operational concept results in a significantly different risk assessment.

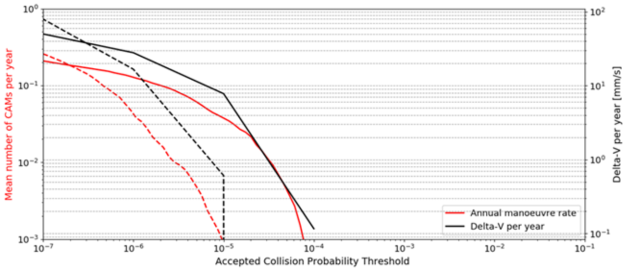

Figure 15: Mean number of CAMs per year and dV used depending on the ACPL for the GEO Insertion scenario, for nominal (dashed lines) and improved (solid lines) operational concepts

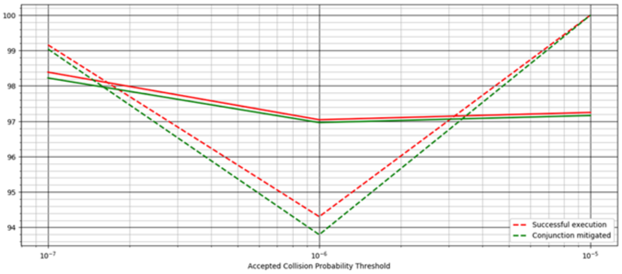

Figure 16: Successful software execution and conjunction mitigation rate depending on the ACPL for the GEO Insertion scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

For this scenario, again, contrary to the GEO Graveyard EOR situation (discussed in section 5.4), longer lead times imply that the conjunction mitigation rate is much higher, above 90% across all ACPLs.

5.4 GEO Graveyard EOR Scenario

The improved operational concept applied for this scenario involves on-board accelerometers which allow to reduce the uncertainty derived from thrusters operation, in contrast with the nominal operational concept where the uncertainty of the thruster is allowed to grow according to the configuration of the error model in Table 4. For this scenario, conjunctions will arise due to the relative motion the primary acquires with respect to the other GEO objects while it is leaving its slot on GEO ring. The manoeuvre profile is such that the orbit's perigee and apogee have cleared GEO after around a quarter revolution, therefore, conjunctions are expected to be encountered at this point of the transfer. This implies that the uncertainty of the system has not had the time to grow that much, so that the risk assessment under a nominal operational concept is not expected to suffer as much compared to other scenarios. This can be observed in figures 17 and 18.

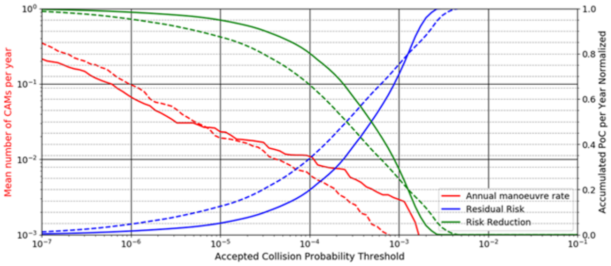

Figure 17: Mean number of CAMs, normalised residual risk and risk reduction depending on the ACPL for GEO Graveyard EOR scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

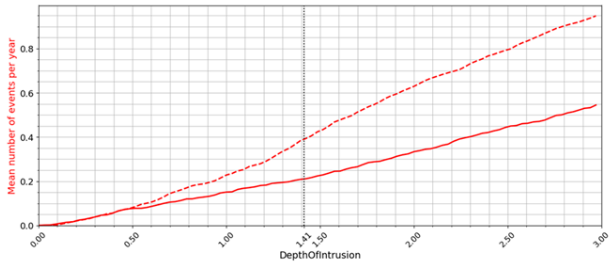

Figure 18: Cumulative histogram of the number of events per year depending on the Depth of Intrusion (Mahalanobis distance) for GEO Graveyard EOR scenario with nominal (dashed lines) and improved (solid lines) operational concepts.

The annual manoeuvring rate is similar for both operational scenarios, with the exception of an observed slight shift of events from the lower ACPL scale to the higher risk end. The reason for this is the improved covariance management, which aids in providing a better risk assessment, attributing a higher risk to conjunctions that under nominal considerations would be found to possess a smaller PoC.

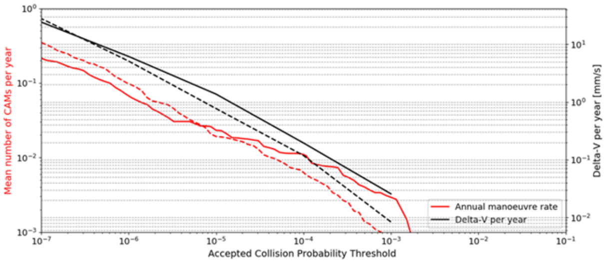

Figure 19: Mean number of CAMs per year and dV used depending on the ACPL for the GEO Graveyard EOR scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

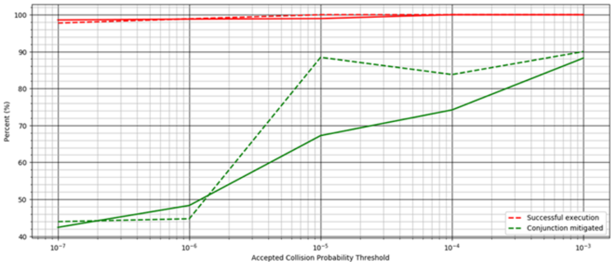

Figure 20: Successful software execution and conjunction mitigation rate depending on the ACPL for the GEO Graveyard EOR scenario, for nominal (dashed lines) and improved (solid lines) operational concepts.

In terms of CAM computation, once again the dV mimics the evolution of the annual manoeuvring rate curve, with dV expenditures per CAM of around 10 mm/s across all ACPLs. Regarding the mitigation rate, a low value overall can be identified, from 40% for an ACPL of 10^{-7} up to below 90% for an ACPL of 10^{-3}. This is in accordance to what was previously explained. The fact that the conjunctions are encountered in the first quarter of revolution leaves small room to manoeuvre. These conclusions are however slightly artificial, as in practical terms, the GEO Graveyard EOR operation would not be started until operators are confident that the transfer manoeuvres would not cause a high-risk conjunction.

6. Conclusions

The introduction of the operational concepts aim to mitigate the uncertainty associated to such long thrusting activities, which impact both the ability of the operator to predict the state of the spacecraft with time (and thus the similarity between the predicted and the flown trajectory) and the accuracy of typical PoC computation methods that rely on a realistic covariance.

The LEO-to-LEO EOR scenario utilised concepts aimed to reduce orbital uncertainties and to delay the CAM decision, and it showcased improvements for both event detection and risk mitigation, compared to the nominal operational concept case. With GNSS coverage, the covariance was kept constant and controlled, allowing for improved tracking accuracy results, leading to a reduction in the number of CAMs per year, for all ACPL values.

The GTO-to-GEO EOR Interval 1 scenario introduces an additional complexity, compared to the LEO-to-LEO EOR scenario. In this case, the satellite resides for most of its orbit outside the coverage of GNSS network. Thus, only for around 40 minutes the object benefits from improved tracking capabilities associated to the operational concept. From then on, the error of the thruster operations is allowed to grow until the next revolution. The operational concept during this part of the orbit relies on on-board accelerometers which aim to mitigate such growth. Therefore, the improved operational concept also introduces a benefit for conjunction events with GEO objects. The GTO-to-GEO Interval 1 scenario overall does show a significant improvement by reducing the required CAMs per year across all ACPLs.

A key difference between the GTO-to-GEO Insertion and GEO Graveyard scenarios was identified. The former will encounter most of the conjunctions near the end of the manoeuvre plan, where the uncertainty has therefore been allowed to grow, while the latter encounters all the conjunctions near the beginning of its transfer. Since both the insertion to GEO ring and its exit happen in less than one day (which is the period of GEO orbit), approximately all the conjunctions encountered in the GEO Insertion EOR are encountered in the last half or quarter revolution, while for the GEO Graveyard EOR scenario, these are encountered in the first quarter of revolution. The difference in propagated uncertainty is significant, considering that the manoeuvring sequence has an impact of hundreds of kilometres on the orbit. In both of these scenarios, the operational concept relies on an on-board calibration of the thruster error through accelerometers, which aids in reducing the uncertainty growth.

As the majority of expected conjunctions are close to the end of the GEO Insertion phase, the improved operational concept has a more significant impact compared to the GEO Graveyard scenario. In particular, a shift of the CAMs per year curve is obtained, revealing many more high-ACPL conjunctions compared to the conventional case. A clear interpretation of this effect is that the mitigated uncertainty growth plays against conjunctions entering the depth of intrusion region, and providing a more realistic risk assessment. It is worth noting that both of these scenarios are difficult to simulate, since the operator may choose to delay or anticipate the manoeuvre to avoid any possible conjunction.

The CAM simulation for each of the detected conjunctions reveal a delta-V trend which follows the CAMs per year curve. The improved risk assessment (related to smaller covariances) is not seen to play a major role in reducing the required delta-V when operational concepts are considered when comparing to the nominal scenarios. In terms of software execution, while it runs successfully in the vast majority of scenarios, the rate of successful risk mitigation is seen to increase with increasing ACPL. If a too restrictive ACPL is chosen (near the lower end of the scale), high risk conjunctions may not be possibly mitigated specially if the timeline ahead for design, uplink and execution is too tight.

Acknowledgements

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Appendix A Operational Concept Scenarios

The following table contains the scenarios using electric propulsion that are being considered along with the operational concepts that apply to each of the scenarios. A subset of these scenarios have been chosen to be analysed and simulated in this paper.

Table A: Summary table presenting the operational scenarios considered mapped to each suggested improved operational concept (in section 2).

Scenario ID	**Scenario Name**	**Propulsion (mm/s^2)**	**Manoeuvre Freq. (days)**	**Mission Examples**	**Improved Operational Concepts**
RL1	LEO-to-LEO EOR Low	~0.1	continuous	Starlink	MA4, MA5, MA6, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
RL2	LEO-to-LEO EOR High	~0.1	continuous	OneWeb	MA4, MA5, MA6, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
RG1	GTO-to-GEO EOR	~0.1	continuous	Telecommunication GEO (e.g., SES 17)	MA4, MA5, MA6, OD2, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
RM1	LEO-to-MEO EOR	~0.1	continuous	G2G	MA4, MA5, MA6, OD2, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
LL1	LEO EOL Low	~0.1	continuous	Starlink	MA4, MA5, MA6, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
LL2	LEO EOL High	~0.1	continuous	OneWeb	MA4, MA5, MA6, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
RG2	GEO Graveyard EOR	~0.1	continuous	MEV-2	MA4, MA5, MA6, OD2, CD1, OW1, OW2, MI5, MI6, IR1, IR2, IR4, IR5
ML1	LEO Mega-constellation Low	~0.1	~1	Starlink	MA4, MA5, CD1, IR1, IR2, IR4, IR5, MI6
ML2	LEO Mega-constellation High	~0.1	~10	OneWeb	MA5, OD1, CD1, IR1, IR2, IR4, MI6
MG1	GEO SK Full EP	~0.1	~1	Telecommunication GEO (e.g., SES 17)	MA4, OD2, CD1, CD2, IR1, IR2, IR4, IR5, MI6
MG2	GEO SK Hybrid EP	~0.01	~1	Telecommunication GEO	MA4, OD2, CD1, CD2, IR1, IR2, IR4, IR5, MI6
ML3	LEO Tube control	~0.1	~1	Science	MA4, MA5, CD1, OW1, OW2, IR1, IR2, IR4, MI6
ML4	LEO Low dV	Limited thrust duration	> 30	Deimos1-2	MA5, OD1, CD1, OW1, OW2, IR1, IR2, IR4
ML5	LEO Low acceleration	< 0.01	> 30	MICROSCOPE	MA5, OD1, CD1, OW1, OW2, IR1, IR2, IR4
ML6	LEO Ground track control	~0.1	> 30	MetOp	MA5, OD1, CD1, OW1, OW2, IR1, IR2, IR4