ASSESSMENT OF COLLISION AVOIDANCE MANOEUVRE PLANNING FOR LOW-THRUST MISSIONS

EXECUTIVE SUMMARY

ELECTROCAM

Prepared by:	Pierluigi Di Lizia Camilla Colombo Michelle Maestrini Andrea De Vittori Juan Luis Gonzalo Joaquín Míguez Manuel Sanjurjo Pau Gago Jorge Rubio Marc Torras Diego Escobar
Authorized by:	Diego Escobar

ESA Contract:	4000135744/21/D/SR
ESA Code:	ES
Code:	GMV-ELECTROCAM-ES
Version:	1.1
Date:	26/08/2024
Status:	Approved

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	04/08/2023	23	First version
1.1	26/08/2024	23	Final version

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. PURPOSE

The purpose of this document is presenting the **Executive Summary** of the Assessment of Collision Avoidance Manoeuvre Planning for Low-Thrust Missions activity.

1.2. SCOPE

This document is applicable to the "**Assessment of Collision Avoidance Manoeuvre Planning for Low-Thrust Missions**" activity.

1.3. CONTENTS

This document contains the following sections:

- Introduction
- Applicable and Reference Documents
- Terms, Definitions and Abbreviated Terms
- Executive Summary
  - Task 1: Critical review of available systems
  - Task 2: Approach to uncertainty evolution
  - Task 3: Operational concepts for low-thrust missions
  - Task 4: Update of the ESA DRAMA ARES Tool
  - Conclusions and future work

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1: Applicable documents

Ref.	Title	Code	Version	Date
[AD.1]	N/A			

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2: Reference documents

Ref.	Title	Code	Version	Date
[RD.1]	N/A			

2.3. BIBLIOGRAPHIC INFORMATION

The following documents have been used as **bibliographic information** in the preparation of this executive summary.

Ref.	Title
[BI01]	Holste, K. et al. (2020). Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer. Review of Scientific Instruments, 91. https://doi.org/10.1063/5.0010134
[BI02]	Saleh, J. H., Geng, F., Ku, M., & Walker, M. L. R. (2017). Electric propulsion reliability: Statistical analysis of on-orbit anomalies and comparative analysis of electric versus chemical propulsion failure rates. Acta Astronautica, 139 (December 2016), 141–156. https://doi.org/10.1016/j.actaastro.2017.06.034
[BI03]	D2.1 Database on EP (and EP-related) technologies and TRL – EPIC-CNES-2.1-RP-D2.1-1.2 – 1.0 – 02/2015
[BI04]	Lev, Dan & Myers, Roger & Lemmer, Kristina & Kolbeck, Jonathan & Keidar, Michael & Koizumi, Hiroyuki & Liang, Han & Yu, Daren & Schönherr, Tony & Gonzalez, Jose & Choe, Wonho & Albertoni, Riccardo & Hoskins, Andrew & Yan, Shen & Hart, William & Hofer, Richard & Funaki, Ikkoh & Lovtsov, Alexander & Polzin, Kurt & Duchemin, Olivier. (2017). The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years.
[BI05]	Gonzalez del Amo, Jose. (2019). Electric Propulsion at the European Space Agency (ESA).
[BI06]	P.S. Maybeck, Stochastic Models, Estimation, and Control, Academic press, New York, 1982.
[BI07]	A. Fuller, Analysis of nonlinear stochastic systems by means of the Fokker–Planck equation, Int. J. Control 9 (6) (1969) 603–655.
[BI08]	J.L. Junkins, M.R. Akella, K.T. Alfriend, Non-Gaussian error propagation in orbital mechanics, J. Astronaut. Sci. 44 (4) (1996) 541–563.
[BI09]	A.D.Cd Jesus, M.Ld.O. Souza, A. Prado, Statistical analysis of nonimpulsive orbital transfers under thrust errors, Nonlinear Dyn. Syst. Theory 2 (2) (2002) 157–172.
[BI10]	Menegaz HM, Ishihara JY, Borges GA, Vargas AN. A systematization of the unscented Kalman filter theory. IEEE Transactions on automatic control. 2015 Feb 16;60(10):2583-98.
[BI11]	Bin Jia, Ming Xin, and Yang Cheng. High-degree cubature Kalman filter. Automatica, 49(2):510–518, 2013.
[BI12]	DeMars KJ, Bishop RH, Jah MK. Entropy-based approach for uncertainty propagation of nonlinear dynamical systems. Journal of Guidance, Control, and Dynamics. 2013 May 13;36(4):1047-57.
[BI13]	DeMars, Kyle J., Yang Cheng, and Moriba K. Jah. "Collision probability with Gaussian mixture orbit uncertainty." Journal of Guidance, Control, and Dynamics 37, no. 3 (2014): 979-985.
[BI14]	Crisan D, Miguez J. Particle-kernel estimation of the filter density in state-space models. Bernoulli. 2014;20(4):1879-929.
[BI15]	Oksendal B. Stochastic differential equations: an introduction with applications. Springer Science & Business Media; 2013 Mar 9.
[BI16]	Kloeden PE, Platen E. Numerical methods for stochastic differential equations. CRC Press; 2018 May 4.
[BI17]	W Rüemelin. Numerical treatment of stochastic differential equations. SIAM Journal on Numerical Analysis, 19(3):604-613, 1982.
[BI18]	F Kenneth Chan et al. Spacecraft collision probability. Aerospace Press El Segundo, CA, 2008.
[BI19]	R.H. Battin, An Introduction to the Mathematics and Methods of Astrodynamics, AIAA, 1999.
[BI20]	A. Gelb, Applied Optimal Estimation, MIT Press, 1974.

Ref.	Title
[BI21]	S.J. Julier, J.K. Uhlmann, H.F. Durrant-Whyte, A new approach for filtering nonlinear systems, in: Proceedings of IEEE American Control Conference, 1995, pp. 1628–1632.
[BI22]	Arasaratnam I, Haykin S. Cubature Kalman filters. IEEE Transactions on automatic control. 2009 May 27;54(6):1254-69.
[BI23]	N. Wiener, The homogeneous chaos, Am. J. Math. 60 (4) (1938) 897–936.
[BI24]	R.S. Park, D.J. Scheeres, Nonlinear mapping of gaussian statistics: theory and applications to spacecraft trajectory design, J. Guid. Control Dyn. 29 (6) (2006) 1367–1375.
[BI25]	R. Armellin, P. Di Lizia, F. Bernelli-Zazzera, M. Berz, Asteroid close encounters characterization using differential algebra: the case of Apophis, Celest. Mech. Dyn. Astron. 107 (4) (2010) 451–470.
[BI26]	G. Terejanu, P. Singla, T. Singh, P.D. Scott, Uncertainty propagation for nonlinear dynamic systems using gaussian mixture models, J. Guid. Control Dyn. 31 (6) (2008) 1623–1633.
[BI27]	Brockwell, P. J. and Davis, R. A. (2016). Introduction to Time Series and Forecasting. Springer.
[BI28]	J.L. Gonzalo, C. Colombo, P. Di Lizia, Analytical framework for space debris collision avoidance maneuver design, J. Guid. Control Dyn., 44:3 (2021), 469-487. https://doi.org/10.2514/1.G005398
[BI29]	Richardson-Little, W., Patterson, C., & Peake, G. (2019, December). Collision avoidance management for Earth observation constellation missions. In First Int'l. Orbital Debris Conference.

3. TERMS, DEFINITIONS AND ABBREVIATED TERMS

The following acronyms have been used across this document:

Table 3-1: Acronyms

Acronym	Definition
ACPL	Accepted Collision Probability Level
CA	Collision Avoidance
CAM	Collision Avoidance Manoeuvre
CDM	Conjunction Data Message
DAGMM	Differential Algebra Gaussian Mixture Model
DISCOS	Database and Information System Characterising Objects in Space
ECI	Earth Centred Inertial
EO	Energy Optimal
EOL	Electric Orbit Lowering
EoL	End of Life
EOR	Electric Orbit Rising
EP	Electric Propulsion
FO	Fuel Optimal
GEO	Geostationary Earth Orbit
GMM	Gaussian Mixture Model
GTO	Geosynchronous Transfer Orbit
HBR	Hard Body Radius
KDE	Kernel Density Estimator
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MISE	Mean Integrated Squared Error
NASA	National Aeronautics and Space Administration
OEM	Orbit Ephemeris Message
PNI	Process Noise Index
PoC	Probability of Collision
SRC	Spherical Radial Cubature
STM	Stochastic Taylor Model
STR	Star Tracker
TCA	Time of Closest Approach
TVD	Total Variation Distance
UP	Uncertainty Propagation
UT	Unscented Transform

4. EXECUTIVE SUMMARY

The current activity is titled **Assessment of Collision Avoidance Manoeuvre Planning for Low-Thrust Missions**, and it intends to evaluate the impact of low-thrust propulsion such as electric thrusters on collision avoidance operations.

Currently, there exists a trend towards the adoption of **low-thrust technologies** like **electric propulsion** in the satellite community due to the important **fuel savings** associated with this technology as opposed to traditional chemical thrusters. Within the low-thrust field, there exist plenty of **different types** of devices, with different purposes and different degree of adoption within the satellite community.

Those devices provide a **low thrust**, which reduces the **reactivity** of the satellites, and increases the impact of the **uncertainty** coming from **long thrusting arcs** on the **uncertainty of orbital predictions**, which are needed for **collision avoidance operations**. Thus, it is necessary to develop means to propagate properly the associated orbital uncertainty, beyond the traditional linear approaches.

It is also necessary to **propose and evaluate** different **operational concepts** suited for conjunction screening and collision avoidance operations with low-thrust, considering the different aspects mentioned above (e.g., low reactivity, continuous-thrust uncertainty) and constraints affecting such devices. Additionally, it is also necessary to develop **modern algorithms** for collision avoidance manoeuvre design, with different properties and for different purposes (e.g., fast computations, refined results…).

Moreover, **satellite mission designers** need to evaluate the impact of the use of such electric devices as part of the mission design process, with **software tools**, like ESA's DRAMA ARES, adapted to those operational concepts for low-thrust, allowing to assess the collision risk associated to a given mission.

The objectives of the **Assessment of Collision Avoidance Manoeuvre Planning for Low-Thrust Missions** activity can be summarized as follows:

- Perform a **survey of the different existing low-thrust types** and the **degree of adoption** of those currently and in the future, and evaluate different operational manoeuvre strategies as well as autonomy approaches.
- Develop a proper **methodology for the propagation of the orbital uncertainty** caused by the uncertainty in the continuous low-thrust provided by the thruster, and suited for the collision risk assessment (e.g. collision probability).
- Propose and assess through simulations and sensitivity analyses different **operational concepts** adapted to the collision avoidance operations with low-thrust devices in different scenarios, considering the **constraints** imposed by such devices, how to perform **conjunction screening** and orbit determination, and also collision avoidance manoeuvres.
- Extend **ESA's DRAMA ARES** software to cover not only satellites with chemical thrusters allowing impulsive manoeuvres, but also electric thrusters for low-thrust propulsion, including also the capability to analyse orbital transfers such as Electric Orbit Raisings where the orbital parameters vary over time.

Each of the objectives above map to one **task** performed as part of the activity, namely:

- **Task 1:** Critical review of available systems
- **Task 2:** Approach to uncertainty evolution
- **Task 3:** Operational concepts for low-thrust missions
- **Task 4:** Update of the ESA DRAMA ARES Tool

The following sections describe the subtasks and results obtained in each of those tasks, concluding with a section devoted to conclusions as well as future work.

4.1. TASK 1: CRITICAL REVIEW OF AVAILABLE SYSTEMS

In this first task an overview of **low-thrust adoption** is performed. Since the first test of electric thrusters in space in 1964 with the suborbital **NASA mission SERT-1** and until 2019, **more** than **500 satellites** had some kind of electric thrusters on-board. The initial applications of these propulsion systems were related to the North-South Station Keeping in geosynchronous orbits, but in the first years of this century, the possibility of using low thrust for **electric orbit raising** (EOR) from **GTO to GEO** became a real option [BI01]. A database has been built up with 156 models of thrusters (developed by industries established in 18 different countries) that either have been flown in space or that are currently under development. The main sources of information for the database are the public datasheets found on the producer's websites. The USA is the main actor in low-thrust systems, and **electrostatic solutions** are the most popular ones. It is interesting to notice that, up to now and according to the considered sources, only thrusters from **four low thrust subclasses** (Hall effect thrusters, gridded ion thrusters, resisto-jets and field-emission electric propulsion) have been flown in space.

A **performance** overview is also carried out in this task. The reliability of the systems is an important feature and there are important differences between estimating it through ground testing and doing the analysis considering the operation in space, as in [BI02]. Integrating the thrusters in the spacecraft allows the analysis of the performance and interaction of the complete system. The main conclusions extracted from the analysis of reliability of electric thrusters performed in [BI02], covering the period between 1997 and 2015 are summarised as follows. Before 2005, electric propulsion had lower reliability than the classic chemical propulsion systems, mainly due to the bad performances of gridded ion engines. In general, HETs have significant better performances with respect to reliability than chemical propulsion. And the gap in reliability between HETs and gridded ion engines is small and seems to be shrinking every year. The performance depends on several aspects. Firstly, the underlying **technology** impacts the **thrust level** and **pointing accuracy**. However, it could also be affected by any of the components of the subsystem and by other subsystems. For instance, some technologies allow controlling the orientation of the beam through the regulation of the magnetic fields. However, most of them will rely on a pointing mechanism [BI03], although they normally do not provide the pointing accuracy, with some exceptions, claiming an accuracy of 0.01º.

Regarding the overview of **operational profiles**, it is based on the available literature and GMV's experience. Electric orbit raisings are characterized by **multi-revolution transfer** lasting several months, and with the **low-thrust actuating continuously** or with some **coasting arcs**. It has been proven to be successful for: GTO to GEO transfers, with more than 40% launch mass savings [BI05] that allow **more powerful payloads** and **more compact designs;** and in LEO to LEO transfers, allowing **secondary payload launch opportunities**, compliance with **disposal requirements** or **extended mission lifetimes** [BI04]. Moreover, electric **graveyarding and disposal** operations are also investigated. In terms of low-thrust profile, these types of transfers with low thrust are similar in nature to those of electric orbit raising, with spiral-like orbits with increasing or decreasing semi-major axis. However, the delta-V required is one or two orders of magnitude bigger than routine station-keeping (SK) manoeuvres. Finally, **orbit maintenance** operations are analysed in LEO (for both observation and comms. satellites) and in GEO, with a specific focus on the possible strategies.

The **autonomy level** is also an important feature of electric thrusters. The overview is focused on the analysis of current or previous cases. The arguably most relevant mission on autonomy was GOCE, flying compensating the air drag permanently. On the specific topic of low-thrust CAMs, the clearest example is Starlink which, in their last report to the FCC reported 25000 collision avoidance manoeuvres for the constellation, although not much is known about the specifics of their system. The use of **on-board CA,** along with the automation it requires, brings several significant benefits when compared to the traditional ground-based approaches that require multiple human interactions. The first is the absence of the majority of the ground-based processes, especially manual ones, such as the CAM decision meeting. The same is true for the rest of the processes, such as **CAM computation** or **post-CAM screening,** which could be largely automated on the ground, but would likely require human intervention at some point during the process. On-board CA also removes the need for guaranteed communication close to the TCA, which may not be available for every operator.

Finally, the data retrieved in the previous analyses from public information on the internet and disclosable information provided by manufacturers are collected to be **integrated in DISCOS**. The **database for low thrust propulsion solutions** contains information regarding the low-thrust propulsion solutions and their performances (thruster type, propellant, mass, power, specific impulse…). The **mapping** between in-flight/flown **satellites** with the **equipped EP propulsion** solutions links in-flight or already flown satellites equipped with electric propulsion with the corresponding thrusters, providing information about the input power, the number of thrusters and the EOR or SK capabilities.

4.2. TASK 2: APPROACH TO UNCERTAINTY EVOLUTION

4.2.1. TASK 2.1: OVERVIEW OF THEORY ON UNCERTAINTY PROPAGATION

Uncertainty propagation (UP) in the field of space trajectory design and operation usually refers to the determination of the probability density function (PDF) (or, at least, the mean and covariance) of a satellite state. Orbital dynamic problems entailing uncertainty can be described by an **Itô stochastic differential equation** (SDE) [BI06]. For a given dynamical system that satisfies a SDE, the time evolution of a PDF $p(x,t)$ over space x and time t is described by the **Fokker–Planck equation** (FPE) [BI07]. However, solving the FPE in orbital mechanics is a difficult task that has not been yet solved satisfactorily. Alternatively, to retrieve a complete statistical description, one may resort to Monte-Carlo (MC) simulation, which provides means for nonlinear and non-Gaussian UP [BI08][BI09]. However, the MC method is also computationally intensive. To avoid these difficulties, many analytical or semi-analytical techniques for orbital uncertainty propagation have been developed in recent years, often providing partial statistical descriptions only. A review can be found in [BI06].

The PDF of the state of an orbiting object can only be well represented by a Gaussian distribution (mean and covariance alone) over short periods. The effects of atmospheric drag and other perturbations rapidly cause the probability distribution of the position and velocity state variables to become non-Gaussian.

A set of **probabilistic-based UP methods,** identified as potentially suitable in terms of accuracy and computational burden, are studied and evaluated numerically. Gaussian UP methods, including UT and cubature schemes, are computationally fast, but subject to severe limitations. A simple extension of Gaussian UP methods that can account for non-Gaussianity in some scenarios, with a relatively low computational cost, is the approximation of the initial PDF of the orbiting object by means of a Gaussian mixture. The components of this mixture can be propagated over time using UT and cubature methods. Even if the number of terms in the mixture is kept fixed, unlike in more sophisticated adaptive methods [BI12] [BI13], a proper choice of the bandwidth of the Gaussian kernels can allow the characterisation of certain non-Gaussian distributions.

Regarding **dynamic-based UP methods**, many techniques to avoid the shortcomings stemming from trying to provide the entire statistical description of a trajectory are investigated: LinCov [BI19], CADET [BI20], UT [BI21], CB [BI22], PC [BI23], STT [BI24], DA [BI25], GMM [BI26], and the direct numerical solution of FPE giving the true evolution of the PDF. As a result of this analysis, two new approaches based on the combination of Gaussian Mixture Models (GMM) and Differential Algebra (DA) are proposed.

4.2.2. TASK 2.2: APPROACH TO UNCERTAINTY PROPAGATION IN PRESENCE OF CONTINUOUS MANOEUVRING

The proposed approach relies on the representation of orbital dynamics with **low-thrust uncertainty** through an SDE [BI15] in Itô form:

$$d\boldsymbol{r} = \boldsymbol{v}dt, \qquad d\boldsymbol{v} = [\boldsymbol{f}(\boldsymbol{v},\boldsymbol{r},t) + \boldsymbol{a}_T]dt + \boldsymbol{G}(\boldsymbol{a}_T)d\boldsymbol{W} \tag{1}$$

where t is continuous time, $\boldsymbol{r}(t)$ and $v(t)$ yield the state (position and velocity, respectively) of the orbital object, $a_T(t)$ is the nominal acceleration vector due to the electric propulsion, the factor $\boldsymbol{G}(\boldsymbol{a}_T)$ is a parametric diffusion matrix that represents the **time-dependent uncertainty in the thrust acceleration** (including magnitude and attitude) and $\boldsymbol{W}(t)$ is a Wiener process (a continuous-time Gaussian process with independent increments [BI15]). The drift function $\boldsymbol{f}(\cdot)$ is deterministic and it includes the drag term and any perturbations in the propagator of choice. The diffusion factor $\boldsymbol{G}(\boldsymbol{a}_T)$ has to be constructed and in this project we have proposed a modelling approach that takes into account the uncertainty in the magnitude and direction of the thrust.

The SDE above has to be integrated numerically. This requires specific methods [BI16]. We have discussed the notions of strong and weak convergence of numerical schemes for SDE integration, and described three relatively simple schemes with different convergence guarantees and different requirements. A strong-order 1.0 Runge-Kutta scheme [BI17] has been implemented for the numerical experiments.

Based on the SDE model above and its numerical implementation, we have a assessed a set of **probabilistic methods** for UP, including Gaussian and Gaussian-mixture approximations. The **Gaussian approximations** have been implemented using two unscented transfer (UT) schemes [BI10] and two spherical-radial cubature (SRC) schemes [BI11] with varying computational costs. Because the dynamical model is stochastic, the propagation of Gaussian distributions, using either UT or SRC schemes yields a Gaussian distribution where the mean and the covariance are random variables. Since these schemes are computationally simple, it is possible to produce multiple runs to average both the mean and the covariance.

A similar approach can be followed to approximate the posterior distribution of the satellite state as a finite **mixture of Gaussian distributions**. In this case, one constructs a kernel density estimator (**KDE**) of the initial distribution using Gaussian kernels [BI14]. Then, these Gaussian components are propagated over time using either UT or SRC schemes, to obtain a finite mixture of Gaussians at the time of interest. We have investigated the effect of the bandwidth of the Gaussian kernels on the UP and proposed a regularisation procedure that can be used to smooth out spurious maxima in the Gaussian mixture.

Regarding **dynamic-based methods**, the **first approach** put forward is called **Adaptive Differential-Algebra Gaussian-Mixture-Model (A-DAGMM)** and it relies on the assumption that any non-linear transformation behaves almost linearly if the domain of interest is sufficiently small. As such, it becomes possible to correctly map one distribution undergoing a nonlinear transformation with many smaller distributions undergoing locally linear transformations. A-DAGMM determines the number of domains necessary to perform the correct mapping adaptively during the propagation by detecting the onset of nonlinearity.

The **second method** proposed **extends DA** to include the possibility of handling process noise in uncertainty propagation. The key idea of the resulting **Stochastic Taylor Model** (STM) approach is to obtain a polynomial expansion of the ODE flow for the state which is endowed with a linearized correction term for the covariance to account for the thrust noise. This can be achieved by manipulating the set of linear ODEs regulating the process and propagating them in the DA environment. These polynomial expansions can be used to map the initial uncertainty while also inflating it.

The envisioned UP methods produce GMMs instead of single gaussians. Consequently, an effective way to represent the geometry of the conjunction is to project each combination of Gaussian Mixture Elements (GMEs) from primary and secondary onto a fictitious B-plane which includes the GMEs even though they happen at different TCAs. To find the correct TCAs two methods have been developed: an exact Keplerian approach, and a Picard-Lindelöf analytic approximation which is less accurate but faster for large GMMs. Additionally, in this work, the short-term encounter hypothesis is formulated: this allows to **compute the PoC between GMMs** as a weighted sum of the PoCs stemming from each combination of GMEs [BI18].

4.2.3. TASK 2.3: ASSESSMENT OF SUITABILITY OF THE SELECTED APPROACH

As part of the benchmarking of the different approaches, both long-thrusting and orbit maintenance **operational scenarios** are considered. Among the operational scenarios involving **long thrusting**, orbit raising activities from low LEO to higher LEO and from GTO to GEO are considered; as well as disposal activities such as LEO disposal and GEO grave-yarding. As part of **orbit maintenance** scenarios, station keeping activities in LEO large-constellations and in GEO are considered. For the analysis of the electric **orbit raising/lowering scenarios**, including disposal and graveyarding, an **optimal trajectory** and **acceleration profile** is generated using **GMV's SW** OPEPOR.

The EOR from **GTO to GEO** is based on a **fuel-efficient trajectory** and two intervals are designed for study (the initial GTO orbit and the end interval near GEO). Similarly, the beginning and the end of the EOR from LEO to LEO are analysed, taking as reference OneWeb's operational EOR trajectory. An EOR scenario raising the orbit from **GEO to a graveyard** orbit 350 km above is also simulated. The design of the **LEO disposal** transfer is based on the strategy put in place by Starlink mega-constellation and the starting interval is studied, where there is higher risk of collision with other satellites of the constellation. On the other hand, an analysis of Starlink public ephemeris is conducted for the design of the **orbit maintenance in LEO** scenario, and the final design scenario is based on frequent (daily) **along-track manoeuvres** to compensate for orbital perturbations (i.e. drag) and keep the constellation relative positions. The **orbit maintenance strategy in GEO** is a better studied case: **North-South (NS)** control manoeuvres are needed to compensate for the effect of the lunar/solar gravitation and **East-West (EW)** manoeuvres control the **orbital period and** the **eccentricity** vector. A simulation tool is used to **include the simulated SK plan**. This tool allows to configure the frequency of the manoeuvres and the acceleration achievable, and outputs the SK plan to meet NW and EW constraints. Conjunction events are simulated in all the aforementioned scenarios for their analysis with probabilistic-based and dynamic-based UP methods.

The **probabilistic UP methods** have been tested against a Monte Carlo (MC) scheme running 5x10^4 random trajectories with the strong-order 1.0 Runge-Kutta scheme for each case of interest. These cases include 8 scenarios and 4 thrust noise levels, leading to a total of 32 state distributions. The results of the MC experiments show that the distributions for different thrust noise levels do not overlap, in general. The size of the spreading along the orbit appears related to the increase in uncertainty during the propagation. A scalar process noise index (PNI) has been defined as a proxy for the increase in uncertainty. The main conclusions of the study are summarised below:

1. Different thrust-noise levels, for propagation times in the order of days, can lead to a completely different characterisations of the state uncertainty. Therefore, a proper a priori characterisation of the noise level is needed for a correct estimation of the uncertainty. Specifically, the thrust-noise level characterisation is critical for collision avoidance operations.
2. Methods behave differently depending on the scenarios. The main aspects of the scenarios that condition the performance of the UP methods are: thrust acceleration level, noise case, manoeuvring time, orbital regime and type of manoeuvre. All these parameters relate to the effect of the process noise in the increase of state uncertainty. It has been shown that the process noise index (PNI) can be used to gauge this increase in a single parameter and one can find two extreme scenarios: LEO SK with small manoeuvring time and thrust level, with a small effect of the process noise in the state uncertainty, and LEO to LEO EOR scenarios with large thrust times and medium thrust levels, with a large effect of the process noise in the state uncertainty.
3. SRC methods present intermediate performance in all scenarios both in uncertainty realism and computational cost. From that point of view, they are the most robust. Figure 4-1 shows numerical results in terms of the total variation distance (TVD) between the state distribution computed via MC and the proposed methods. The maximum TVD is always less than 0.15 for the SRC methods, and the influence of the PNI is lesser than in the other UP methods.
4. KDE methods are computationally costly compared to Gaussian approximation methods. They outperform the schemes for large PNI but are less efficient for low PNI, as shown in Figure 4-1. The KDE approximations with coarse band-with yield lower TVD for low PNI, while for high PNI the bandwidth appears less relevant.
5. UT methods enjoy the lowest computational cost of the considered methods. Figure 4-1 shows that they can attain small errors (in terms of the TVD), however their performance degrades quickly with increasing values of the PNI. For a large PNI (long manoeuvres, large uncertainties in the thrust model, or large values of thrust), UT methods are not able to represent correctly the state uncertainty.

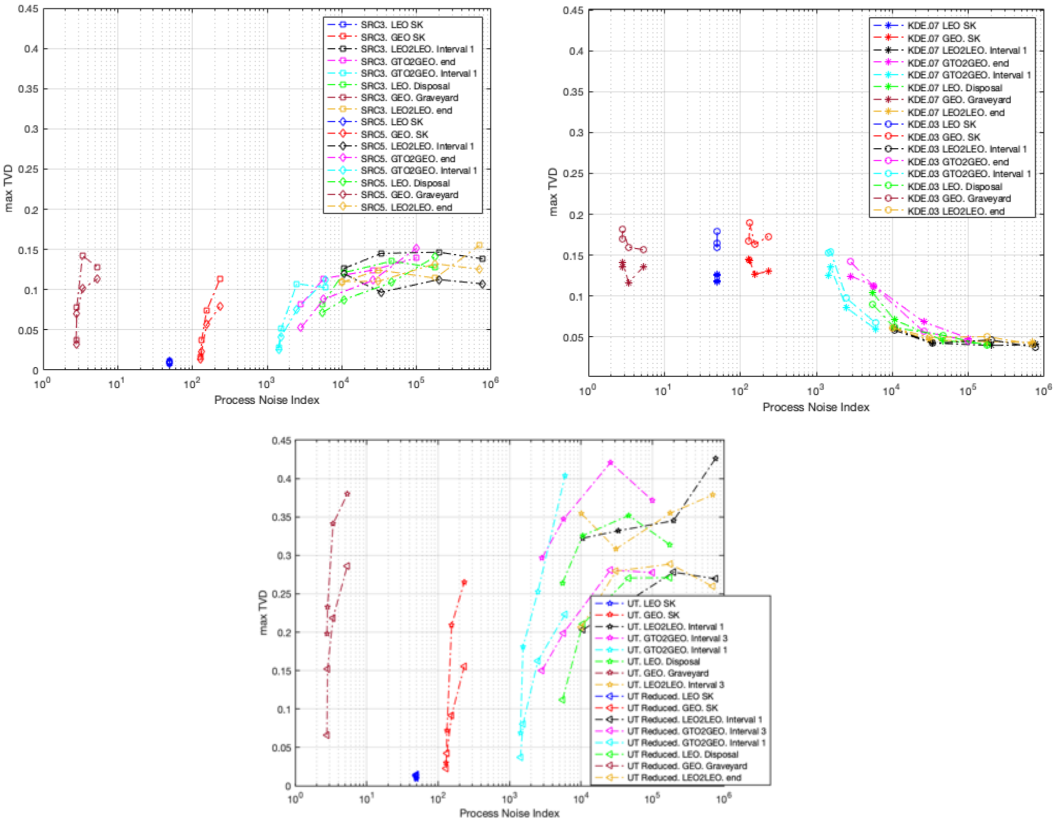
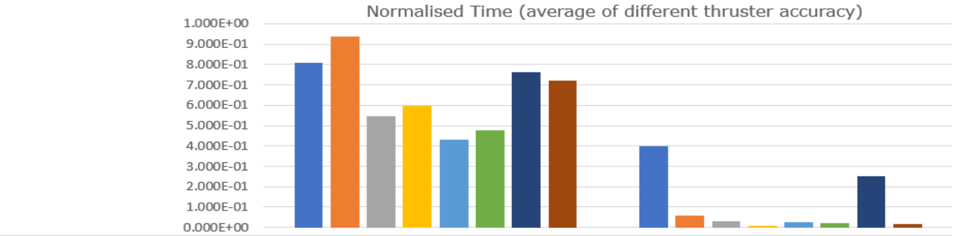


Figure 4-1: Performance of the algorithms SRC3, SRC5, KDE with "fine" bandwidth (0.3) and "coarse" bandwidth (0.7), UT and Reduced UT, in terms of maximum TVD, as a function of the PNI for all the scenarios and all the thrust noise levels.

On the other hand, a summary of the computational times for the two proposed **dynamic UP methods** on the analysed test cases is reported in Figure 4-2.



■ LEO to LEO. Interval 1.	STM	A-DAGMM
■ LEO DISPOSAL. Interval 3.	8.082E-01	3.997E-01
■ LEO SK.	9.394E-01	5.941E-02
■ GTO to GEO. Interval 1.	5.473E-01	2.909E-02
■ GTO to GEO. Interval 3.	5.981E-01	6.874E-03
■ GEO SK.	4.324E-01	2.466E-02
■ LEO to LEO. Interval 3.	4.784E-01	2.320E-02
■ Graveyarding	7.624E-01	2.528E-01

Figure 4-2: summary of computational times for dynamics-based UP methods.

According to the results presented for every test case, one can conclude that STM method is more costly in terms of computational time, however its cost is not dependent on the noise of the thruster, nor on the level of non-linearities. Conversely, both methods show performance degradation for the estimation of the total distribution for degraded thruster accuracy. Despite of this, the estimation of the mean state remains almost unchanged for varying thruster performances. In addition, A-DAGMM shows a dependency of the computational time with the level of thruster uncertainty and with increasing nonlinearities.

The results show that the hyperparameters of both methods can be fixed for similar scenarios. However, they may vary even for the same orbital regime if the propagation is particularly different, as in the case of the station keeping or graveyarding.

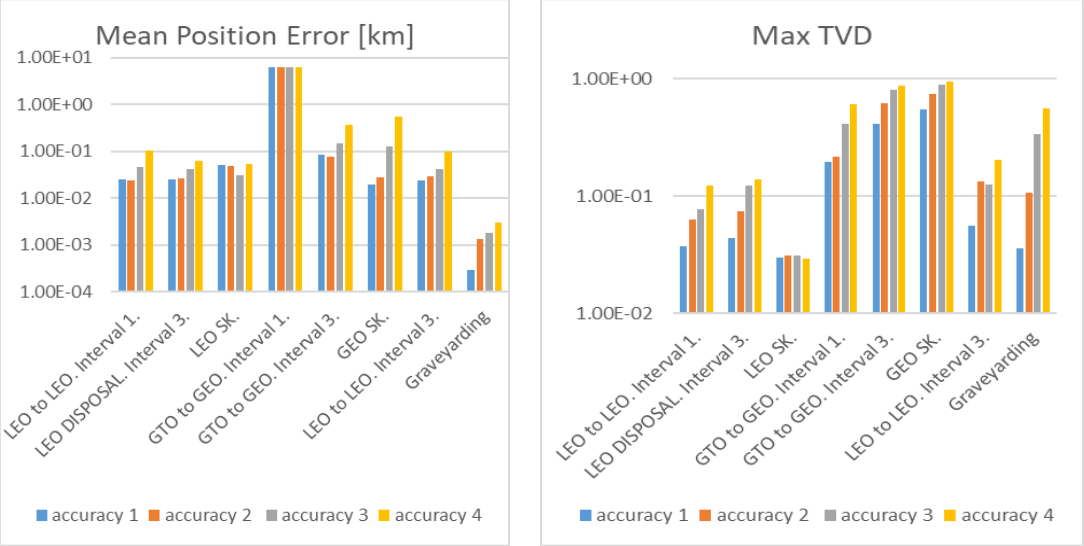


Figure 4-3: Mean position error (left) and TVD (right) for A-DAGMM across different scenarios and varying accuracy levels of the thruster

After the extensive analysis of all proposed probabilistic- and dynamics-based methods, the results show that DAGMM offers the best performance (on average) in line with UT methods in terms of computational cost. Conversely, KDEs and STM methods seem to be the most computationally expensive techniques. In addition, UT methods work best for low process noise as do dynamics-based methods in general, while KDEs are better suited for propagations where higher uncertainties are involved. SRC shows a middle ground performance level both in terms of accuracy and computational cost. When looking at the PoC computation results, dynamics-based methods are always close to the value obtained through a linear propagation, which can be explained by the small errors in terms of mean state obtained by the propagation process. Conversely, the stochastic propagators impact the final geometry of the conjunction causing a PoC dilution (up to 0).

4.3. TASK 3: OPERATIONAL CONCEPTS FOR LOW-THRUST MISSIONS

In previous tasks, analyses have been performed on the adoption and performances of electric propulsion systems, as well as on methods for orbital uncertainty propagation in the presence of low-thrust manoeuvre uncertainty. This **Task 3** focuses on defining **operational concepts to tackle the problem of collision avoidance for missions with low-thrust propulsion systems** for various mission phases, ranging from long-thrusting cases such as EOR/EOL to routine operations with frequent station-keeping manoeuvres.

4.3.1. TASK 3.1: CONSTRAINTS ANALYSIS

The study starts with an analysis of the constraints associated to electric propulsion systems on the collision avoidance process. The following classification for CA operations constraints is proposed here: CA constraints, orbital constraints, attitude constraints and propulsive and power constraints. For each of them a literature review is performed.

The **CA service provider response time** is analyzed with missions like MICROSCOPE, the IRS satellites, and Deimos-1 and Deimos-2. The **satellite operator operational overheads** have two main relevant aspects for CA at ESOC: the need for **personnel on-call** (experts and mission managers, even outside of nominal working hours) and the assessment of CAM **impact** on **science** and **mission** duration, for which the **payload downtime** has a direct impact on the profitability of the mission, and also CAMs have recognised impacts on mission duration due to the additional fuel usage.

The limitations related to **up-link opportunities of CAM** are determined both by operational constraints of **station** contacts, but also depend on the **technologies** present in the communications equipment on the **platform**. Alternative communication paths for sending the CAM command exist, but these are viable options only if the satellite platform has the appropriate communications equipment to receive information through these routes.

Regarding the **propulsion capabilities**, the main constraint is represented by the **maximum available thrust** of the platform. Additionally, the **thrust direction** could be limited by various causes, like the configuration, orientation and location of the thrusters in the platform. Generally, the thrust direction can also be limited by having orientable or fixed thrusters, as well as by blinding constraints for sensors and instruments and thermal reasons. Another important limitation might be related to the **firings** of the engine itself, such as minimum or maximum thrusting durations. This limitation can be given due to operational procedures, such as scheduling aspects of the propulsion subsystem, or even by the thrusters themselves. Overall, **low-thrust propulsion subsystems** limit the maximum achievable delta-V with a CAM. Also, the closer in time the manoeuvre is performed to the TCA, the higher the delta-V needed to obtain a certain reduction in criticality is, as the effect of the CAM cannot accumulate over more time. These two aspects together imply there may be times close to TCA when the delta-V required to reduce the event criticality below thresholds is higher than what the low-thrust system can provide. In such cases, the manoeuvre needs to be performed earlier.

In terms of **station keeping and orbit maintenance constraints**, certain missions are designed to perform orbit control manoeuvres (OCMs) much more frequently than others, so missions with frequent OCMs could combine one of these with a CAM, given favourable conditions, or the CAM could be executed after a programmed OCM. In the case of constellation management, alternative orbit control strategies may arise, for example, keeping the spacecraft within the same orbital tube, as it is well described in [BI29]. Station keeping constraints in GEO typically require the satellite to remain within a well-defined latitude and longitude slot. Finally, other constraints that are also analysed in this work are frequent **eclipsing periods**, **energy storage and electrical power constraints**, and the avoidance of forbidden locations and/or intervals in the Earth orbital **environment** like the Van Allen belts.

4.3.2. TASK 3.2: APPROACH FOR CONJUNCTION SCREENING

For this analysis, different aspects are considered for different operational scenarios. Each operational scenario together with the approach for conjunction screening is defined by the following aspects: **orbital regime** (LEO, MEO, GEO), **mission phase** (EOR, orbit maintenance, or disposal) and reference orbit, and type of **low-thrust** propulsion system (HET, ion engine, FEEP, cold-gas, etc.) and associated **uncertainty** levels in thrust level and pointing, **operational cycle** and **level of autonomy** used to run the mission, **sensors** used for orbit determination, **CA service providers** used (18th SDS, EUSST, LeoLabs, etc.) and limitations imposed by each of them (e.g. screening volume, screening period), **satellite communications means** used (own or ground-station, satellite rely systems, etc.), **metrics used for collision risk** categorization (miss distances, PoC, SPoC) or where (i.e. satellite, control centre, CA service provider) each of the CA processes are performed.

All the aspects above are used to evaluate the **accuracy** and **timeliness** of the **orbit and covariance estimates and predictions** used for the **conjunction screening**, which in turn allows evaluating the **level of uncertainty** with which the conjunction screening is performed as a **function of time to TCA**.

The **operational cycle** has an important impact on the conjunction screening process. The **sensor data available** for the orbit determination is critical for the **accuracy** at the start of the propagation and has an impact on the prediction accuracy. In LEO, the dynamical models used in the orbit determination process are affected by the **drag model errors**, which can reach high values very fast. And the **frequency** of the **orbit determination** has also an impact on the uncertainty after propagation.

In the presence of **manoeuvres**, the orbit uncertainty in the prediction of the conjunction is affected by the thrust uncertainty. The effect is roughly proportional to the impulse size, the typical error in the thrust and the time of the manoeuvre until the TCA. For scenarios with very frequent or almost continuous manoeuvres, like **EOR**, this effect becomes the dominating one in the uncertainty propagation. In fact, in EOR the **errors introduced in the thrust modulus** are found to produce the largest differences in the radial and along-track directions. In the cross-track direction, uniform errors in the out-of-plane angle have been found to produce orbital differences of a similar magnitude to thrust modulus errors, particularly in the initial interval of GTO to GEO transfers, presumably due to the effort of the manoeuvre profile to not only increase the semi-major axis but also reduce the inclination of the orbit. In **orbit maintenance** scenarios, for example in LEO, with the higher frequency and the **extended duration** of low-thrust manoeuvres, the uncertainties associated with the primary object grow rapidly and can even surpass the uncertainties of the secondary object. If the uncertainty is large enough at TCA, there is also the **risk of events being undetected**, even though it is possible to make up for the uncertainty of the trajectory by defining larger conjunction screening volumes. With large uncertainties there is also the risk of **dilution of probability**.

Collision Avoidance service providers are tasked with detecting the **potential collision events,** involving an active spacecraft, by executing the **conjunction analysis** against a catalogue of space debris. This catalogue is maintained with **SST sensor observations**. The conjunction screening process shall be performed anytime the operational orbit for the satellite is updated (after new orbit determination or new orbit control manoeuvres are planned) or the catalogue itself is updated. The orbital information of the primary is normally provided by the satellite operator. It is generally provided daily for LEO satellites, and for MEO and GEO satellites the frequency in which the orbits are provided ranges from daily to weekly. For the secondary, when a conjunction is detected, there is a whole process to improve the accuracy of the CDM. Usually, **sensors are commanded** to track the secondary object to have **more accurate and more recent data**.

The **level of autonomy** of the satellite is also analysed in detail due to its relevance on the operations and its impact on the capabilities for CA. Having the satellite to automatically compute and execute the manoeuvre **removes the need to take the decision on-ground earlier**, i.e. it can be delayed until close to the TCA since no uplink of the manoeuvre to the satellite is required. Doing this on-board **reduces a several hours long process** to something that can be done almost instantly based on predefined thresholds.

Regarding collision risk metrics, several factors can be considered to **evaluate the risk of a conjunction**. The most common are the geometry and the PoC parameters. However, there are others that can contribute and can help to provide a better risk assessment when dealing with low thrust propulsion. For example, the Mahalanobis distance can be used to detect if a conjunction is within the **dilution of probability**, and a maximum **time to TCA** can be limited to **avoid false positives** and wait for new updates that reduce the uncertainty.

As part of this task, all **operational scenarios for electric propulsion** identified and analysed in Tasks 1 and 2 are evaluated with the previous criteria, and in those where typical conjunctions become non-actionable, a change in the typical approach for conjunction screening is proposed, to **avoid undetected high-risk events** or **reduce the likelihood of dilution of probability** by decreasing the level of uncertainty as a function of the TCA. The operational concepts proposed to **reduce the uncertainties** caused mainly by the **frequent and/or long thrust arcs** associated with low thrust propulsion are the following: defining planned manoeuvres in a local reference frame and angle tagged, a frequent calibration of thruster performances, a feedback control with GNSS, an accelerometer feedback control, the optimal consideration of coasting arcs, and the consideration of thruster outages. The **operational concepts** that improve the **accuracy** of the estimated orbit in an **orbit determination** are the following: using more accurate measurements, receiving support from sensor networks, and increasing the OD frequency. Finally, the operational concepts devoted to improving the **selection of the screening volume** in electric propulsion cases are: the automation of the CA service provider interface, and performing a robust risk analysis.

4.3.3. TASK 3.3: APPROACH FOR COLLISION AVOIDANCE

The main considerations needed for the definition of a CAM operational concept have been analysed in detail. Regarding the **thruster considerations,** the **acceleration levels** exerted upon the spacecraft can vary widely from mission to mission, the **thrust orientation** is affected by errors in the satellite's attitude and the slew rate, and there are **thruster limitations** like the minimum and maximum thruster times, eclipses or the transient time. Several **operational concepts** have been proposed and analysed taking into consideration how they are applied and which benefits they provide. The proposed concepts have been divided into four main groups depending on their area of improvement upon traditional approaches: concepts to **delay the CAM decision time**, concepts to **reduce mission impact**, concepts to **reduce the operational workload**, and concepts to **increase robustness**. Some of those **operational concepts** considered are: late telecommand paths to postpone the decision time, CAM design on-board, early CAM, Keep the deviation from the original orbit bounded (box control), shut-down engine during EOR/EOL, modify planned manoeuvres in EOR/EOL or SK, etc. Additionally, three main CAM design methods are proposed: **full CAM optimisation** (the CAM Optimal Control Law is optimized with high-fidelity models), **efficient CAM optimisation** (problem is simplified with hypotheses like fixed thrust direction and with simplified models like semi-analytical ones), and **selection among default CAMs** (some pre-defined CAMs are tested for the most common cases and the most adequate is used).

As part of this activity, several **analytical and semi-analytical approaches to CAM design** for Energy-Optimal (EO) and Fuel-Optimal (FO) firing strategies are also designed. In addition, each optimization metric is combined with two PoC models (i.e., Gaussian and GMM) and two firing direction constraints: radial and tangential. Indeed, radial manoeuvres proved to be more effective than the tangential ones for just-in-time manoeuvres. Consequently, 8 different combinations of cost function, thrust direction, and final PoC constraint have been obtained. Moreover, two dedicated CAM methods to deal with Gaussian and GMM distributions at TCA have been developed for EOR scenarios. In these cases, the exact switch-off time to impose a PoC limit is found with a bisection method such that the PoC boundary function is satisfied.

This work also provides an **analytical low-thrust CAM model** based on the single-averaging of the dynamical equations that can be applied to CAM characterization, parametric analyses, and CAM design when combined with a suitable approximation for the control law. For the latter, a pseudo-optimal, piecewise-constant control law is proposed based on an analogous model for impulsive CAMs [BI28]. The single-averaged CAM model consists of three steps. First, the orbit modification due to the CAM is quantified through the change of its vector of Keplerian elements. Analytical expressions for the variation of Keplerian elements under a continuous thrust acceleration are derived by averaging the Gauss's planetary equations over one revolution in eccentric anomaly. Second, a linearized relative motion model maps this variation of elements into changes in position and velocity at the TCA. Finally, the outcome is projected in the nominal encounter plane at TCA, and the PoC is quantified.

On the other hand, a **numerical direct optimization** approach to collision avoidance manoeuvre design have been proposed involving the formulation of a non-linear programming problem (NLP) which is passed on to a NLP solver (e.g., IPOPT). A direct method favours from an arbitrarily complex definition of the cost function, and an eased introduction of constraints. In the proposed method, the manoeuvre is discretized at a set of nodes, specified at evenly spaced true anomaly intervals. At each of these nodes, the value of the in-plane and out-of-plane thrust angles are set as the unknown optimization variables. With the value of these two angles, the thruster pointing direction can be built at each of the nodes. If the thruster operates at a predefined acceleration level, the three components of the delta-V can be built at each of the nodes. The effect of the manoeuvre on the orbit of the spacecraft is evaluated through a **simplified propagation** that combines the **STM** and an **analytical Keplerian propagation**. This direct approach for CAM optimization does not have any limitation on the number of constraints.

As part of this task, an extensive analysis of the performances of the CAM design methods is performed. For this purpose, an auto-correlation model for the process noise due to the low-thrust is adopted [BI27]. The test results show no significant variation when adopting an infinitesimal time scale. Conversely, using an infinite time correlation coefficient it is observed that longer warning times usually allow for earlier manoeuvres, hence causing a reduction in cost of the nominal CAM, while also causing a large increase in final uncertainty. Moreover, it is observed that the largest variations in CAM cost are caused by the convergence to different local minimum of the numerical methods adopted. Subsequently, the single-averaged method is applied to study the impact of manoeuvre duration, timing, and acceleration on CAM design. LEO test cases show an oscillatory pattern on PoC evolution, related to the positions of CAM and CA with respect to apocentre and pericentre. The amplitude of these oscillations is related to the characteristics of the nominal orbit (particularly, the eccentricity). The results are consistent with those from the EO method, in terms of acceleration and PoC. In higher orbital regions the required thrust is smaller, and the duration of the thrust and coast arcs are shorter due to the longer period, and the higher ratio between thruster acceleration and gravitational acceleration.

4.3.4. TASK 3.4: SIMULATIONS

A **simulation environment** has been prepared to test the performance of the operational concepts for **conjunction screening** and **collision avoidance** in the presence of **continuous thrust**. To that end, the realistic trajectory of low thrust satellites in key operating stages of their life cycle, which involve long thrusting and station keeping activities, and that have been previously derived as part of the project, have undergone, as the real flown trajectory of a given satellite, a screening against a TLE catalogue, involving objects of different regimes.

The introduction of the **improved operational concepts** aims 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 which rely on a realistic covariance. This way, **two sets of predicted trajectories and covariance evolution** (at a given time before TCA) have been generated, one which resembles typical operating conditions and one which incorporates the improved operational concepts to be tested.

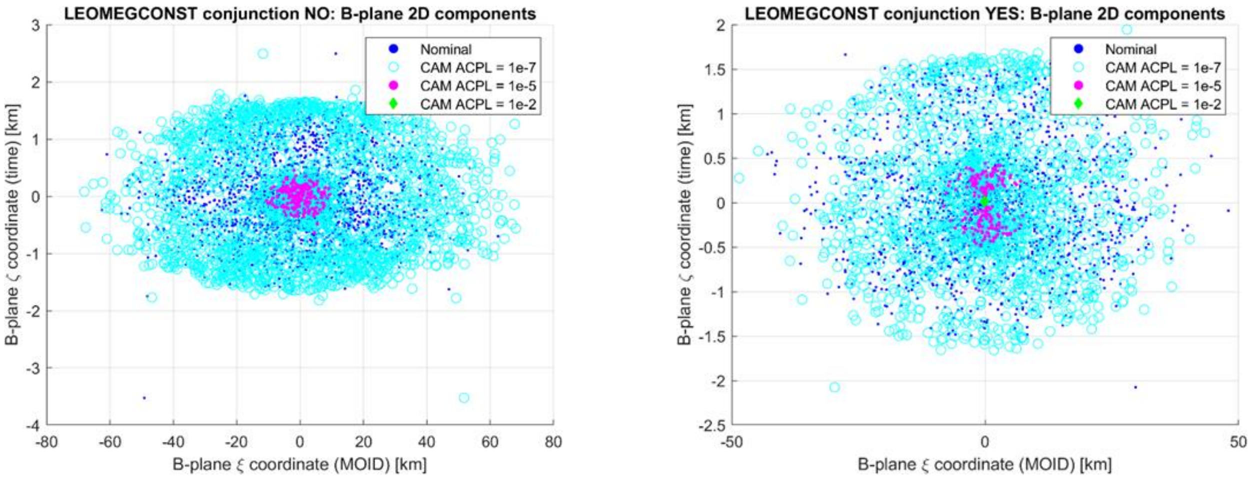
For the **collision avoidance risk assessment**, the effect of the improved operational concepts has been observed to be different **depending on the scenario**. For the **low LEO to high LEO** transfer, under GNSS coverage and thus allowing a constant and controlled covariance, the improved tracking accuracy results in a reduced number of CAMs per year across all ACPLs. The results for the **initial interval of the GTO to GEO** transfer do show a significant improvement by reducing the required CAMs per year across all ACPLs. For the **graveyard** scenario, due to the fact that most of the conjunctions are detected early in the transfer, the associated uncertainty is still small and the introduction of the improved operational concept does not weigh in significantly. On the contrary, for the **GEO insertion**, since the conjunction are mostly observed near the end, the improved operational concept does in fact have a noticeable impact and provides a more realistic risk assessment. The **CAM simulation** for each of the detected conjunctions reveals 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 improved operational concepts are considered, as compared 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.

4.3.5. TASK 3.5: SENSITIVITY ANALYSIS

Several tasks are conducted during an **extensive sensitivity analysis** for varying parameters of the conjunctions and CAM design methods. The operational concepts developed in this project are analysed on a large number of simulated CDM scenarios. The ballistic CDMs are analysed first and **two concepts of operations** are considered: the **STANDARD** one (NO) and the **NEW PROPOSED** one (YES). The CDM cases are characterised in terms of the miss distance at TCA, the relative velocity at TCA, the PoC and the representation of the relative position vector on the B-plane at TCA.

For all cases analysed the miss distance (and, in general, B-plane coordinate) increases in general for the cases where CAM is performed, and the effect is more visible for lower ACPL. Moreover, thrusting arcs are shorter in GEO than in LEO when using lower ACPL. Aside from a limited number of cases that do not converge due to numerical issues, almost all scenarios achieved convergence. Some of the CDMs in the NEW PROPOSED approach failed to produce a CAM due to the short warning time: this could be accounted for by minimizing the PoC in case an exact ACPL is not achieved. For the STANDARD operational concepts in GEO most of the solutions for CAM are clustered at full number of revolutions plus half period due to the sufficient warning time to exploit the best manoeuvre location. Conversely, LEO cases display clustering well in advance. When analysing the new operational concepts, the LEO manoeuvres are not clustered and performed as early as possible due to the shorter warning times. For the cases with EOR it is difficult to identify any regular pattern associated to the orbit geometry. This is probably due to the additional constraints in the way the CAM is performed, which does not allow to leverage the characteristics of the close approach. Also, for the EOR scenarios a few cases fail to enforce the desired ACPL due to the short notification time that characterizes this operational concept.



a) B-plane representation. Concept of operations: standard

b) B-plane representation. Concept of operations: new

Figure 4-4 Characterisation of the LEOMEGCONSTCAM scenario of the ballistic case.

4.4. TASK 4: UPDATE OF THE ESA DRAMA ARES TOOL

ESA's DRAMA ARES (Assessment of Risk Event Statistics) analyses collision events between an operational spacecraft and debris objects orbiting the Earth. More specifically, ARES computes **collision statistics** (annual collision probability, mean number of avoidance manoeuvres, delta-V, propellant mass fraction…) using the **debris environment model** of MASTER, These collision statistics are very useful for mission planning.

One of the objectives of the current activity consists in extending the ARES software to cover not only satellites with chemical thrusters allowing impulsive manoeuvres, but also **electric thrusters for low-thrust propulsion**. Moreover, the analysis of the collision risk encountered throughout a low-thrust transfer, e.g. from GTO to GEO, as it flies through regimes with significantly different debris environment properties is of special interest. In this type of scenarios, the covariance at the time of closest approach (TCA) needs to consider one of the most relevant sources of uncertainty for low-thrust platforms, which is the uncertainty introduced by the thruster.

After the developments implemented in this activity, ARES offers the possibility to compute the statistical collision metrics not only for a single target orbit of the spacecraft defined in terms of the Classical Orbital Elements, but also for a **pre-computed trajectory of a low-thrust transfer** provided in an Orbit Ephemeris Message (OEM) following CCSDS standards. The analysis of a trajectory is based on its discretization in a series of relevant intermediate orbits. The statistical collision metrics are obtained for each of these **intermediate orbits** and the final collision metrics associated to the complete transfer are obtained by making a weighted average of the partial results. The **weighted average** is based on the residence time of the spacecraft on each reference orbit. This approach allows to account for the **non-uniform distribution of the space debris** environment on an orbital regime basis: for example, more intermediate orbits are taken in LEO than in other regimes with lower debris density. The long thrusting arcs of low-thrust transfers have a significant impact on the size of the covariance of the spacecraft at the conjunction time. In these cases, the **uncertainty at the TCA** mainly depends on the uncertainty introduced by the **thruster** (in terms of errors in the thrust magnitude and the pointing direction), the **orbital state** (mainly affected by the perigee altitude and the eccentricity) and the **time since the last orbit determination**. Therefore, in case of electric orbit raising (EOR) or electric orbit lowering (EOL) scenarios, the user has the possibility to choose between a set of pre-defined **operational concepts**:

- **GNSS based OD + feedback control**. When under GNSS coverage, the covariance of the spacecraft will be maintained within tight bounds throughout the trajectory.
- **Autonomous manoeuvre feedback control**. The spacecraft is able to execute the transfer manoeuvre plan taking advantage of on-board measurement devices such as accelerometers, and therefore mitigating the uncertainty growth derived from thruster operations.
- **Uncontrolled**. Nominal operating conditions. There is no measure to mitigate the uncertainty growth associated to the transfer manoeuvre plan.

ARES has also been extended to compute the statistical delta-V for **low-thrust platforms**. When an electric propulsion system is considered, the effect of a collision avoidance manoeuvre (CAM) cannot be regarded to happen at a single instant of time. Therefore, it is necessary to take into account the fact that a low-thrust manoeuvre for avoidance purposes may be executed during a **significant portion of an orbital revolution**. Consequently, the delta-V of a continuous manoeuvre cannot be computed analytically by relating the nominal orbit and the desired post-CAM orbit that reduces the collision risk below a given threshold, as it is computed for the impulsive case. An **iterative algorithm** has been implemented to integrate the effect of a low-thrust CAM. It is based on dividing the manoeuvre arc into **sub-arcs** in which impulsive delta-Vs are applied, thus approximating the low-thrust and continuous characteristics of the manoeuvre plan of an electric thruster. **Keplerian dynamics** are used for the propagation of the manoeuvre effect to the TCA of the conjunction. Finally, a **secant method** is implemented to determine the low-thrust delta-V that produces the required miss distance at the TCA of the conjunction. An alternative method for a faster computation of the low-thrust delta-V has also been implemented. This simplified approach is based on the assumption of circular orbits and does not need the integration of the delta-V over the manoeuvring arc, thus providing a computational performance equivalent to that of the impulsive CAMs.

The **validation plan** of the software upgrade is based on unit and system tests. **Unit tests** are executed by a dedicated Fortran module and cover the new procedures (i.e. subroutines and functions) implemented to provide the aforementioned functionality. **System tests** are complete ARES executions and the results obtained for the collision statistics allow to ensure the correctness of the new developments and the consistency with the existing software functionalities. Once the tests are successfully passed in the test environment, they have been added to the Continuous Integration/Continuous Delivery (CI/CD) pipeline in GitLab to be executed automatically as **non-regression tests**. To that end, previously validated references of the outputs of the tests have been used.

4.5. CONCLUSIONS AND FUTURE WORK

The objective of this activity has been to assess the **collision avoidance manoeuvre planning for low-thrust missions**, given the current context towards the massive adoption of such a propulsive option. To that end, the first step involved a **survey** of the existing low-thrust thrusters, producing a detailed **characterisation** of the thruster's **performance** and **uncertainty**, and an identification of typical **operational profiles** of orbit raising, disposal and orbit maintenance with low-thrust, for subsequent analysis, as well as of different level of autonomy achieved for collision avoidance operations with low-thrust. As a by-product of the survey, the collected information has been collected and prepared for import into DISCOS.

The low reactivity of low-thrust platforms increases the impact of the uncertainty coming from thruster, especially during long thrusting arcs. Hence, uncertainty propagation methodologies have been investigated. Both **probabilistic-based** and **dynamics-based** methods have been evaluated in terms of **computational cost** and **total variational difference** (TVD) as a proxy of uncertainty realism, for different operational scenarios and degree of process noise. Computational cost in terms of Monte Carlo normalised run can be as large as more than 50% for KDEs and STM methods. Considering uncertainty realism, **UT** is better applicable for **low process noise index** (PNI) scenarios, while **Cubature** shows a more **stable** behaviour with increasing PNI. Alternatively, **KDEs** are seen to perform better for **high process noise** cases. **Dynamics-based** methods are seen to follow a trend **similar to** that of the **UT**. In terms of PoC computation capabilities, dynamics-based approaches are seen to yield values close to the results of linear propagation. However, it has been found that the stochastic modelling in probabilistic-based methods of the thrust acceleration can significantly affect the conjunction geometry, especially in high PNI scenarios.

To the survey conducted in the first task indicating the performance and uncertainty characterisation of low-thrust thrusters, and the performance and limitations of the uncertainty propagation approaches in the second task, a third work package has incorporated the identification of **constraints** which affect the **collision avoidance process**, particularly for low-thrust platforms. These are grouped into CA constraints, orbital constraints, attitude constraints and propulsive and power constraints. Additionally, a number of operational concepts are derived. For **conjunction screening**, these are grouped in terms of whether they tackle to reduce the uncertainty involved in manoeuvre execution, orbit determination, conjunction screening volume selection according to expected uncertainty levels. For **collision avoidance**, these are derived with the intention to: delay CAM decision time, to reduce mission impact or to reduce the operational workload. In this context, the benefits of having computationally efficient analytical/semi-analytical CAM design methods as an initial guess for higher fidelity but expensive numerical methods is also tested, displaying positive results in the less demanding scenarios (high-LEO, MEO, GEO), while drag-modelling is seen to play an important role for lower orbits.

A **simulation environment** which replicates operational procedures has been built, including the preparation of a statistically significant amount of conjunctions via the screening of the different **operational scenarios** identified in previous tasks against multiple **TLE catalogues** and replicating the **operational cycle for the primary**, in which each of the applied **operational concepts** produces **different operational cycle performances**.

The effect of the improved operational concepts has been observed to be different depending on the scenario. For scenarios involving merely **SK activities** on LEO and GEO the effect of the improved operational concepts is **barely** noticeable. For scenarios involving long periods of continuous thrust and long propagation times, such as the early or last stages of a **GTO-to-GEO transfer**, the risk analysis reveals a decrease in the required annual manoeuvring rate above an order of magnitude for each accepted collision probability level when resorting to the improved set of operational concepts.

These simulations are then subject to a sensitivity analysis with the objective of extracting the effect on the CA process of parameters such as time to CA, total-dV, time to next OD, orbital parameters… revealing different patterns in terms of manoeuvre execution clustering, B-plane behaviour and successful mitigation rate varying for different operational concepts and orbital regimes.

The final task of the project gathers the knowledge acquired in the previous tasks to prepare a **low-thrust update of ESA's DRAMA ARES** tool. This upgrade has concerned three main **new functionalities**: the processing of a **pre-computed trajectory** of an EOR/EOL transfer to obtain the collision statistics referred to that trajectory, the consideration of the **uncertainty introduced by the thruster** (e.g. due to errors in the thrust magnitude or in the pointing direction) to evaluate the collision risk corresponding to different operational concepts, and the modelling of **low-thrust** collision avoidance **manoeuvres** to mitigate the collision risk.

As **future work**, the following tasks have been identified:

- **Keeping an updated low-thrust thruster databases.**
- **To study and develop autonomous strategies on-board and/or ground/on-board**, which can work with little supervision.
- **Inference algorithms for calibrating the thrust acceleration noise level**.
- **Stochastic integrators in orbital uncertainty propagation**. Investigate alternative structures in the diffusion (i.e., process noise) term, study the effect of correlations in the process noise…
- **Extend dynamics-based methods for uncertainty propagation**, by applying Adaptive Domain Splitting both for STM and A-DAGMM approaches, or substituting the cartesian coordinates with a parametrization based on orbital elements to better preserve the Gaussian property during propagation.
- **Robust collision avoidance manoeuvres.**
- **Concerning analytical and semi-analytical CAM design models.**
    - Models tailored for last-minute manoeuvres.
    - Inclusion of constraints in the design of analytical and semi-analytical CAMs.
    - Extend the CAM design models to include return of the spacecraft to its nominal orbit.
    - Extend the CAM design models to manage active vs. active conjunction.
    - Develop software for on-board autonomous CAM design and execution.
    - A convex optimization-based approach to get fuel-optimal CAMs in an orbit-raising scenario.
    - Finding the optimal thruster switch-off time along a reference thrust history to avoid the collision.
    - Combined CAM and Station-Keeping (SK) routine with convex optimization-based approach.

END OF DOCUMENT