ADVANCING AUTONOMOUS COLLISION AVOIDANCE: THE CREAM-IOD MISSION FOR SAFE AND SUSTAINABLE SATELLITE OPERATIONS

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ABSTRACT

The CREAM In-Orbit Demonstration (CREAM-IOD) mission marks a significant milestone, bringing together the advancements from all CREAM-related initiatives. The CREAM-IOD mission aims to demonstrate, using a small satellite, a next-generation platform providing essential technologies to support safe operations in the space debris environment, incorporating key capabilities for collision avoidance with applicability to small satellites.

The objective of this phase A activity was to devise a system design capable of accomplishing this. The identified drivers for CREAM-IOD were: i) Representativeness for highly congested regions in terms of space traffic; ii) Compliance with zero debris policies released by the Agency; iii) High Technology Readiness Level (TRL); iv) Low-cost System and v) Compatibility with a launch in 2027-2028.

To wrap-up the system design, a model-based system engineering (MBSE) approach has been followed and successfully deployed during the activity.

1 BACKGROUND

With the emergence of mega-constellations comprising thousands of satellites and the increasing risk of collisions with space objects and debris, traditional ground-based methods for orbit maintenance and collision avoidance may soon become unsustainable. To address these evolving demands, new approaches and technologies are essential. The Collision Risk Estimation and Automated Mitigation (CREAM) is a set of activities within the Space Safety programme of the European Space Agency, focusing on advancing technologies for automated ground operations, on-board autonomy and coordination to support spacecraft navigation in increasingly crowded orbital environments.

In this context, GMV brings extensive experience in developing collision avoidance technologies for both ESA and private clients. GMV's notable contributions to ESA include the development of CRASS, ESA's first operational collision avoidance tool, and leading roles in the various ESA CREAM initiatives, including:

- CREAM#1, where a standalone system has been developed focused on the ground-based automated collision risk assessment (CA) and collision avoidance manoeuvre (CAM) design algorithms and methodologies.
- CREAM#2, where some of the usual collision assessment algorithms and methodologies have been developed to increase the autonomy of the mission and perform the autonomous late commanding of the collision avoidance manoeuvre (CAM) through the implementation

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

of the on-board CAM system in a Zynq 7030 board.
- CREAM#3 activity, where a collision avoidance coordination system between active satellites (i.e., a "rule-of-the-road") has been designed and is currently under development.

2 AUTOMATED COLLISION AVOIDANCE

In the frame of ESA CREAM cornerstone and the afore-mentioned activities, two of the main activities developed have been the on-ground and on-board approaches to automated collision avoidance processes. Both approaches will be deployed and experimentally demonstrated in orbit during the CREAM-IOD mission.

2.1 On-Board Collision Avoidance System

The On-Board Collision Avoidance System (OCAS) encompasses a set of algorithms developed by GMV, to be loaded on-board the satellite, and capable of propagating the primary and the secondaries' orbits, assessing the potential conjunction events, evaluating the conjunction risk and compute the collision avoidance manoeuvre as well as the return manoeuvre, screening the results of the manoeuvre plan against subsequent potential colliders:

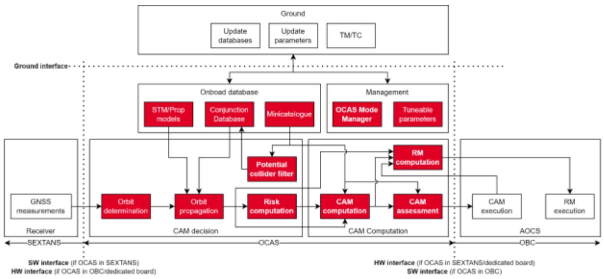

Figure 1. OCAS architecture

The greatest advantage of OCAS is its readiness in-orbit and quick computation time. While the typical collision avoidance process involves having the same steps on-ground, involving different actors, with heavier computations, to obtain a manoeuvre plan that needs to be commanded then to the satellite when a contact window is open, OCAS presents the possibility of roughly assessing the need for manoeuvre in-orbit, producing a manoeuvre plan for the mission in few minutes without needing to interact with ground.

It is important to note that periodic updates of tuning parameters and catalogues from the ground are necessary to ensure OCAS operates with the most recent available data. In addition, note that propagations and computations made on-board are highly dependant on the computational capacity of the on-board equipment, so OCAS consists of reliable but simplified algorithms. Fine-detail computations and the most accurate assessments are better obtained from the on-Ground Collision Avoidance System (GCAS).

2.2 On-Ground Collision Avoidance System

The On-Ground Collision Avoidance System (GCAS) encompasses a set of GMV products dedicated to automated collision avoidance processes. Leveraging extensive expertise gained at GMV as providers of ground segment solutions, particularly in Flight Dynamics, Space Situational Awareness, and Traffic Management, an automated collision avoidance system has been devised comprising two main modules: ***AutoCA*** and ***AutoSTM***.

AutoCA is the ground software developed in CREAM activities which investigates the computation of collision assessment and collision avoidance manoeuvres based on multiple user inputs. By means of Artificial Intelligence-Machine Learning (AI/ML) technology, it predicts the Probability of Collision and Conjunction Geometry. The first step of ***AutoCA*** is detecting the collision based on the internal catalogue and thresholds provided by the satellite operator. This step makes use of a Smart Sieve filter and a user defined safety ellipsoid. The second step, in case of plausible collision, ***AutoCA*** computes the Probability of Collision and Conjunction Geometry based on a high-fidelity algorithm. In parallel, based on the historical Conjunction Data Messages (CDMs) of a satellite operator and its trained model, an AI/ML prediction of the secondary object State Vector and Covariance Matrix can be applied. If an alert is raised, the CAM recommendation process starts, based on the constraints provided by the satellite operator (platform, operational, ground), and multiple optimisation solutions can be provided. A final check on the computed manoeuvre plan is done to guarantee that the risk is indeed mitigated by executing the manoeuvre.

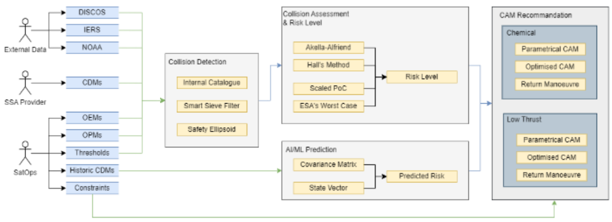

*Figure 2. **AutoCA** architecture*

Meanwhile, ***AutoSTM*** is a centralised system used for coordination between the satellite operators and other entities. The coordination process is represented not only by file and information exchange but also by a multi-agent system trade off based on the information provided by each of the satellite operator for its spacecraft.

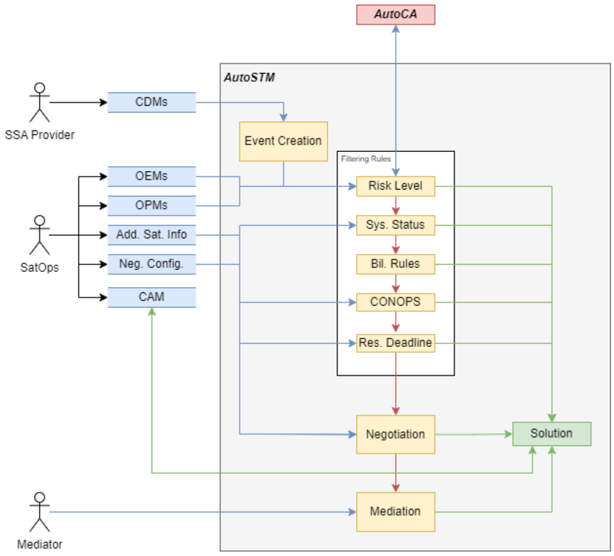

*Figure 3. **AutoSTM** architecture*

AutoCA and ***AutoSTM*** can leverage on a strong, already operational Ground Segment. From Flight Dynamics System (FDS), allowing for scheduled, automatic planning of Orbit Determination and Orbit Propagation tasks that could be added in the loop to ***AutoCA*** and ***AutoSTM***, to Mission Planning System (MPS) and Mission Control System (MCS), enabling scheduled, planned upload to the spacecraft, complete functionalities with minimum human intervention in the process can be deployed.

3 SYSTEM CONSIDERATIONS

In the sequel of the above outlined activities and the automated collision avoidance systems to be tested in-orbit, the CREAM In-Orbit Demonstration (CREAM-IOD) mission marks a significant milestone, bringing together the advancements from all CREAM-related initiatives developed by ESA over recent years. The aim of the CREAM-IOD mission is to fly a small satellite as example and demonstration for a next generation platform that provides technologies supporting safe operations in the space debris environment, with all the required key capabilities for collision avoidance, guaranteeing wide applicability. The key hardware and software components have been devised to be compatible with multiple standards and frameworks, as well as potential future constellations, to boost its adoption.

3.1 System Drivers

During CREAM-IOD phase A activity, a set of drivers was defined to lead the system design, based on the user needs provided by the Agency. These are:

- Representativeness for highly congested regions in terms of space traffic;
- Compliance with Zero-Debris policies released by the Agency in [1];
- High Technology Readiness Level (TRL);
- Low-cost and wide applicability;
- Compatibility with a launch in 2027-2028.

3.2 System Capabilities

To achieve CREAM-IOD mission goals, the following capabilities had to be ensured during system design:

- **<u>Payloads</u>**. Consisting mainly of the automated collision avoidance systems (described in previous section), to which the platform subsystems shall answer to:
    - **On-board Automated Collision Avoidance System**: set of algorithms dedicated to CAM processes for a fully autonomous approach on-board. CREAM#2 heritage provides this mission with a TRL 5 set of encapsulated algorithms.
    - **On-ground Automated Collision Avoidance System**: set of ground functionalities dedicated to CAM processes for a fully autonomous approach from ground. CREAM#1 and CREAM#3 heritage provide the mission with TRL 7/TRL 9 ground capabilities.

- **<u>Platform</u>**. A spacecraft capable of providing the adequate performance must be envisaged for the mission. Not only for CREAM experiments, but also for regular operations like station-keeping, disposal, zero debris policies, etc. Given the specialized nature of this IOD mission, particular emphasis has been placed on the following subsystems, which directly support the CREAM experiments:
    - **Guidance, Navigation and Control/Attitude Determination and Control System (GNC/ADCS)**: needed for in-orbit control (either regular operations or ground-commanded experiments), it is also envisaged to support the on-board algorithms in the CAM computations.
    - **On-Board Computer (OBC)**: as the GNC/AOCS, needed for in-orbit control (either regular operations or ground-commanded experiments), it is also envisaged to support the on-board algorithms in the CAM computations.

- ○ **Communication**: the spacecraft will need to communicate with ground (either directly or via data relay) to enable the automated CAM approach from ground and the late-commanding path. In addition, Inter-Satellite Link (ISL) will also be considered to test the negotiation and coordination procedures from CREAM#3 with a secondary spacecraft (in this case, the secondary will be simulated from ground).

- ○ **Propulsion**: given the ample spectre of new propulsion systems available by the industry, it is important that the propulsion system not simply performs the CAMs, but that it is adaptable to different configurations. This will enable verification of the system for different scenarios (mainly high vs low thrust).

- **Ground Segment**. To properly validate and verify CREAM-IOD results, some of the experiments will require almost simultaneous track of activities from ground. A ground segment with operational experience in collision avoidance and precise orbit determination context is essential for the activity development.

- **Launch**. Availability of suitable launch opportunities within the proposed mission timeframe is essential. Launch capabilities include compatibility with the preselected mission concept in terms of operational orbit, timeframe, mechanical/electrical/thermal interface with final spacecraft design as well as budget-wise.

4 SYSTEM TRADE-OFFS

Once the scope of the system design was established, different architectures were pondered and traded off to come up with the optimum baseline.

One of the first design items was the operational orbit selection for CREAM-IOD. As per mission drivers, the experiments needed to take place in a representative environment of a congested area, not because actual conjunction events are envisaged during the demonstration (which would indeed put both the mission and others at risk in case of failure), but to test the system performance under relevant environmental and operational conditions. Considering this, a low Earth orbit (LEO) was selected for the CREAM-IOD mission. This orbit is representative for a wide number of the most populated constellations, where conjunctions events are frequent and for which speeds are considerably higher than for other orbital regimes such as geostationary (GEO).

Then, from the different heights to be considered in LEO band, two additional trade-offs were extracted. On the one hand, locating CREAM-IOD in the lower ranges of LEO rendered compliance with Zero-Debris policies [1] easier, lowering the delta-V needs to access 5-years natural decay or even automatically granting it depending on the platform final design. On the other hand, launches to LEO sun-synchronous orbits (SSO) amounted to 40 during 2023 (mostly to heights comprehended between 450 and 600 km), presenting CREAM-IOD with a wide number of launch possibilities, leveraging on ridesharing, reducing the launch costs. Therefore, the orbital height was left as an open parameter to be frozen when a convenient launch is procured, given the flexibility for CREAM-IOD to accomplish its goals in a range of heights.

Automatically linked to the selection of the lower heights of the LEO band (i.e., 450-600 km), three mission elements were narrowed down. First, the radiation environment to be withstood by the platform remained reasonably accessible for small platforms, not requiring an extremely hardened shielding as it would occur with higher heights.

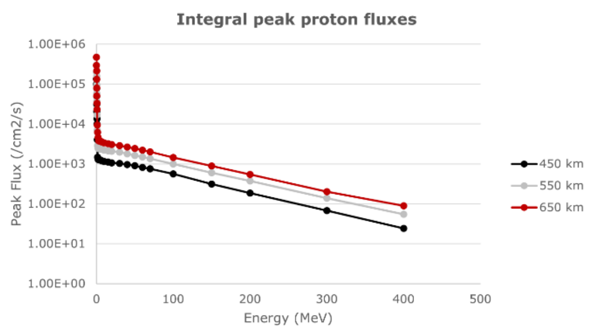

Figure 4. Integral peak proton flux for LEO region 450-650 km

Second, the collocation of the spacecraft on a low SSO ensures a good communication scheme from ground with polar stations but less convenient contacts with non-polar stations. Find hereafter a graphical depiction of the ground contacts for a pre-defined set of stations (i.e., Svalbard, Kiruna, Inuvik, Troll and McMmurdo):

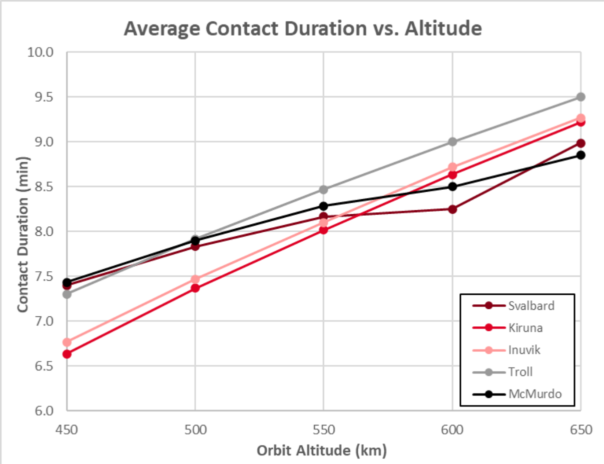

Figure 5. Average contact duration vs SSO altitude

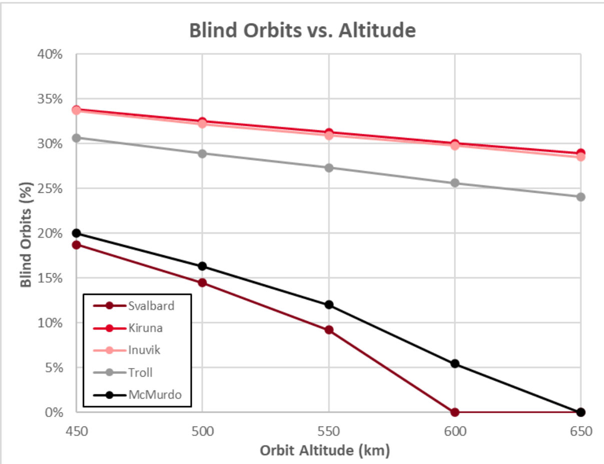

Figure 6. Blind orbits vs SSO altitude

This led the design towards the inclusion of a data relay option to enhance the communications scheme to guarantee late-commanding path testing.

Third, the delta-V needs for the mission can be minimised. Since the goals accomplishment can be achieved in a wide range of operational orbits and there are no limitations on local time of the ascending node (LTAN) for specific ground tracks repetitions, the only manoeuvres foreseen for the spacecraft are:

- Regular collision avoidance manoeuvres (that is, outside of CREAM-IOD experiments);
- Manoeuvres due to experiments;
- Deorbit manoeuvre (perigee lowering) to ensure natural decay in 5 years if not already compliant in the eventual operational orbit.

The next item in the mission design was the platform and its principal subsystems. Targeting the lower LEO band, the main drivers for the platform were to achieve a concept design compatible with the automated collision avoidance systems envisaged as payloads while keeping it low-cost and high TRL. The clear conclusion was the prioritization of commercial off-the-shelf components (COTS), minimising the needs for development, qualification, testing and integration, towards a feasible launch in the 2027-2028 window. This contributed to the selection of a CubeSat platform, for which several COTS components are already available and for which the manufacturer of the Consortium, Alén Space, had already performed the necessary validations, reducing costs and risks. Special mention must be made to ADCS, OBC and communications systems.

The ADCS guarantees the spacecraft control throughout the entire mission, enabling nominal, payload and contingency operations. Particularly, the following modes have been foreseen for CREAM-IOD:

- The idle mode will be active when ADCS action is not required.
- The de-tumbling mode will use de-tumbling controller to dampen the angular motion of the satellite. Mode will be activated after orbital injection.
- The safe mode will use de-tumbling controller to dampen possible angular motion of the spacecraft. Mode will be used in emergencies or if regular modes fail. Mode will be triggered by on-board FDIR or directly from the ground by contingency message.
- The acquisition mode will be used to determine the initial attitude of the satellite, stabilize, and recover satellite from the power upsets and emergencies.
- The nominal mode will use 3-axis stabilization to point spacecraft along desired direction, using the attitude guidance algorithm as a reference. Mode will be used during normal operation of the satellite, e.g. pointing, Sun-pointing, station-keeping and de-orbiting. Mode will be also in charge of the ground CAM execution during satellite normal operation.
- The OCAM (on-board collision avoidance manoeuvring) mode will use fine 3-axis stabilization to point satellite along the desired direction together with OCAM algorithms.

Table 1 ADCS Modes

Mode	Prerequisites	Fallback Mode
Idle	N/A	N/A
De-tumbling	N/A	Idle
Safe	N/A	Idle
Acquisition	De-tumbled platform	Safe
Nominal	Stabilized platform Acquired attitude	Safe
OCAM	Stabilized platform Acquired attitude	Safe

In the following picture a preliminary ADCS modes diagram extracted from Capella MBSE model is shown:

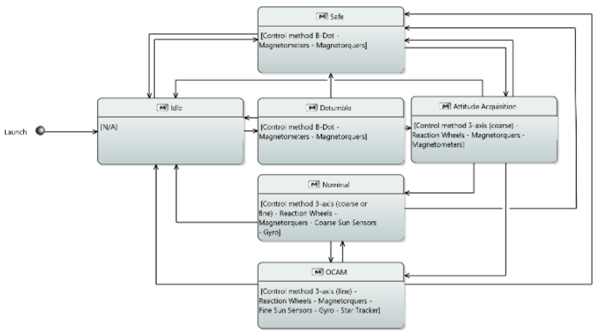

Figure 7. CREAM-IOD ADCS Modes

While traditional orbit determination processes take place on-ground, the on-board automated collision avoidance system (OCAS) requires a precise orbit determination in real-time, on-board in order to feed the OCAS algorithms with the latest spacecraft position and velocity. This is essential to benefit from the greatest strength of OCAS: its fast-decision process relying on most recent information. Therefore, one of the key elements of the ADCS system is the on-board GNSS receiver, SEXTANS.

SEXTANS is a software defined GNSS receiver which provides accurate position, navigation and timing information to support multiple spaceborne applications, suitable for use onboard CubeSats, microsatellites or micro-launchers, whether individual satellites, multiple satellites or mega constellations. It can be either deployed standalone or readily integrated in an existing OBC.

Leveraging on Alén Space TRISKEL OBC (combination of OBC and TTC integrated in a single PC104 module for nanosatellites, it is based on a Cortex-M7 microcontroller for the OBC and another independent Cortex-M7 microcontroller for TTC that manages the radio interface), SEXTANS and the rest of the ADCS algorithms can be embedded and deployed via TRISKEL, reducing the system complexity and easing the internal interfaces. Given the capabilities of TRISKEL, it can simultaneously serve as platform OBC, increasing synergies.

The communications subsystem has a significant relevance in CREAM-IOD. Although the mission does not require the level of data download required by, for instance, Earth Observation missions, the late-commanding path imposes several constraints on the subsystem design. The late command in the collision avoidance manoeuvring context is understood as the latest manoeuvre plan that can be sent up to the spacecraft before reaching the conjunction event, either because no other ground contacts with margin with respect to the conjunction event are foreseen until the time of closest approach (TCA), or because the system manoeuvring concept of operations cannot cope with a commanded plan sent later.

In addition, to increase the system reliability and robustness, a fast, highly available channel to abort automatedly calculated manoeuvres has been considered as indispensable as well, accounting for an exhaustive survey undertaken with different satellite operators, who emphasised the need for such an approach.

Therefore, the late-commanding path requirement compels CREAM-IOD communications subsystem to grant access from ground at any desired time. Instead of fine-tuning the orbit of the mission to achieve high coverage or devising an oversized network of ground stations, the strategy selected is to leverage on data relay to guarantee ground access whenever needed. In order to do this, the analysis on the late-commanding path performed during CREAM#2 activities was used as starting point to determine that, the best option for CREAM-IOD mission is to incorporate on-board an ISL user terminal compatible with Iridium constellation, justified by the mission orbit, platform power, mass and volume capabilities.

The last critical item identified in the design is the propulsion subsystem. CREAM-IOD aims at demonstrating the feasibility of the automated collision avoidance processes for a wide range of platforms and missions. Therefore, it was needed to take into account the essential differences the propulsion types posed and how they affected the CAM process.

As it is well known, low and high thrust propulsion systems are different in nature. While high thrust systems are consolidated in the space sector, most of them are chemically based, and capable of relying a thrust in a very short time at the expense of a significant propellant mass (which results in very low specific impulses), low-thrust systems are electrically based, requiring a much lower amount of propellant at the expense of lower thrust levels and longer burn times (which results in very high specific impulses):

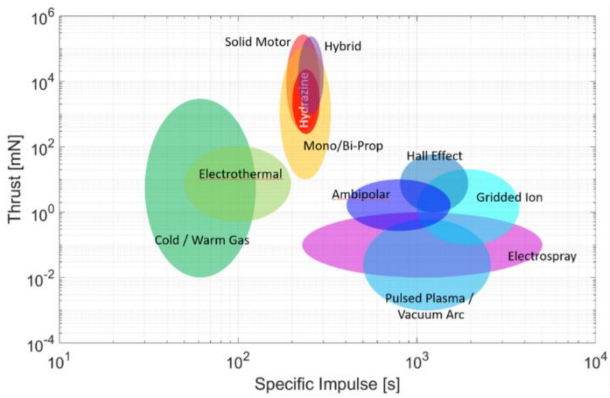

Figure 8. Propulsion Systems [2]

Consequently, low thrust missions present manoeuvring concept of operations entailing several challenges. The decision time is directly affected by the amount of time required to complete the manoeuvre (i.e., hours in order of magnitude compared to the few minutes high-thrust present), but also because of the preparation time the electrical thrusters demand. Cathode beds heating up or progressive thrust levels (i.e., burning profiles), are only a couple of the main differences with respect to high-thrust systems that directly impact the collision avoidance process timeline.

During the CREAM-IOD design phase, the option of carrying both low-thrust and high-thrust propulsion systems was evaluated. This way, direct in-situ experiments could be performed via both methods. However, the increase in cost and mission complexity, alongside the fact that most of the mission experiments are devised to be carried out at software level without actually executing the manoeuvre plan, led the system engineering team to discard the option. To mitigate the lack of true low-thrust system, the chemical propulsion system selected foresees pulse-modulated thrusting. This thrust mode will enable the mission to emulate low-thrust scenarios in terms of collision avoidance timeline whenever needed and achieve at least an adequate level of representativeness.

5 SYSTEM BASELINE CONCEPT

Taking into account all the different trade-offs presented above plus some other less relevant, the final mission concept envisaged for CREAM-IOD mission consists of:

- OCAS and GCAS. Experiments of both systems will be carried out during the mission.
- Operational orbit within LEO lower band. The final height will depend on the launch procurement agreement, which will allow to minimise the cost and maximise the launching opportunities without impacting the spacecraft design. The major change associated to the orbit selection is the potential need to include in the delta-V budget the lowering manoeuvre to guarantee deorbit within 5 years in agreement with the Zero-Debris policies [1]; nevertheless, there exists the same probability of acquiring an operational orbit with a natural decay already compliant with the policies.

Table 2 Example Delta-V for 450 km SSO

Orbit	CAMs	Experiments	Deorbit	DV
SSO 450 km	0.22 m/s	1.65 m/s	-	1.87 m/s

- No station-keeping to be performed while in-orbit. Since there is no specific need for a ground contact pattern nor a particular ground track control for experiments, the mission will save delta-V needs by dropping the option to perform station-keeping manoeuvres.
- Ground Station as a Service (GSaaS). It allows to decouple the ground segment infrastructure from the core mission concept, benefiting from high TRL, low cost and flexibility due to the amount of available networks, empowering the late-commanding path needs.

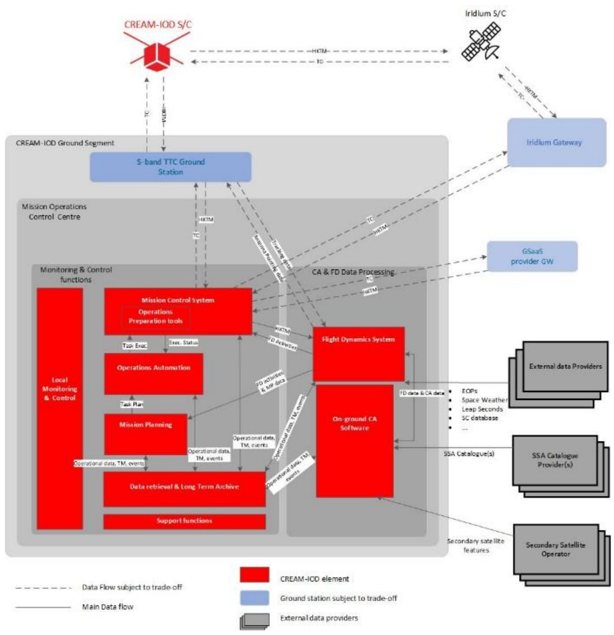

Figure 9. Ground Segment architecture

- ISL Data Relaying for late-commanding path. In addition to GSaaS, an ISL terminal will be on-boarded to enable Iridium constellation as late-commanding path for those points of the mission when no direct contact with ground is available a-priori and manoeuvre commanding/aborting is needed.

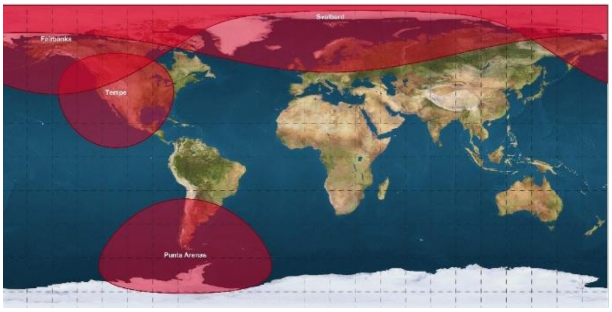

Figure 10. Gateway stations for Iridium Network

- CubeSat by Alén Space. The platform selected for the mission is a CubeSat manufactured by Alén, leveraging on several COTS for small platforms, with high TRL and low cost, but robust enough to achieve the needed mission performance.

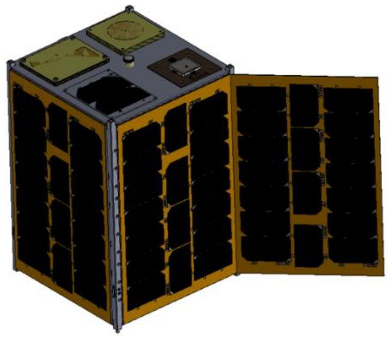

Figure 11. CREAM-IOD Platform

6 SYSTEM STUDY CONCLUSIONS

The final conclusions of this phase A system study were that:

- The different elements of the mission baselined concept are in disposition of acquiring the adequate TRL by the start of phase C,
- The mission concept is in disposition of achieving the proposed timeframe of launch in 2028, and
- Most importantly, the automated collision avoidance systems (both on-ground and on-board approaches) will be ready to successfully carry out the different experiments envisaged for the in-orbit demonstration.

Overall, the system concept is feasible, robust, and ready to advance to the next phase, ensuring successful in-orbit demonstration.

7 BONUS TRACK: MODEL-BASED SYSTEM ENGINEERING

7.1 Introduction

A Model-Based System Engineering (MBSE) approach has been deployed for the CREAM In-Orbit Demonstration mission, involving all stakeholders in the consortium. The combination of DOORS and Capella, supported by Excel and GitLab as MBSE tools, has been consolidated across several projects within GMV and is now established as the standard MBSE environment:

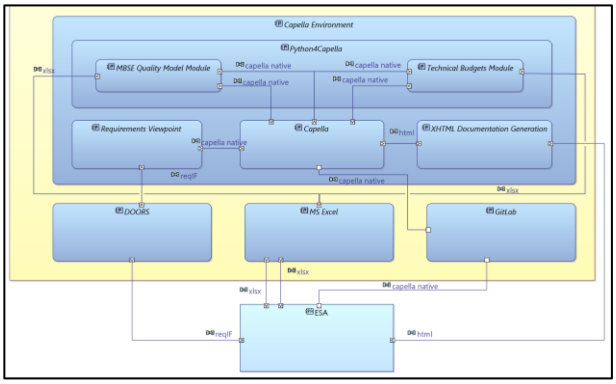

Figure 12. MBSE Approach

Capella is an MBSE, opensource tool developed by Thales Alenia that provides the means to formalize system specifications and architectural designs relying on the ARCADIA method and its own metamodel based on ecore. This tool does not only provide a graphical environment to model the architecture but guides the user along the ARCADIA architectural levels, which progressively adds complexity to the System design and architecture. ARCADIA (ARChitecture Analysis and Design Integrated Approach) is a system modelling method whose aim is to progressively guide the specification and architecture of the System of Interest by addressing different viewpoints. It is important to distinguish that, while Capella is an MBSE tool, ARCADIA is a system modelling method which is tool-agnostic (although Capella is explicitly designed to follow it, other tools could be used to follow ARCADIA, e.g. Cameo Systems Modeler):

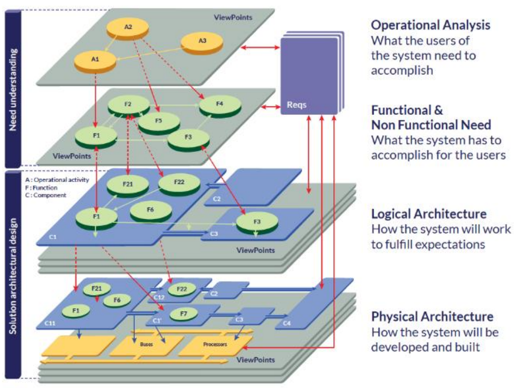

Figure 13. ARCADIA Viewpoints

The system has been modelled as follows:

- **Operational Analysis**: this layer is built to provide a top-level view of the project context. Actors and entities involved in the project are identified, as well as the capabilities required from the system. Moreover, operational activities are defined to describe the automated CAMs operation at a high level by means of an Operational Activity Interaction Blank diagram.

- **System Analysis**: the functional architecture of the system is defined in this layer. The whole mission is treated as a black box that interacts with external actors, thus showing interactions between the system and its contextual actors. Missions and capabilities are identified, being the latter linked to actors involved in their performance. In this layer, requirements are also introduced at the system level.
- **Logical Architecture**: the system is now treated as a white box and three segments are identified, namely space, launch and ground. All segments are broken down into several logical components taking on several functions of the systems that have been transitioned from the System Analysis layer. If applicable, requirements are allocated to logical components, which account for the system's subsystems including comms, thermal, payload…
- **Physical Architecture**: the physical layer accounts for the structure of the physical system and for its behaviour. Logical components are transitioned down as Behaviour Physical Components that allocate the system's functions, and Node Physical Components are defined to capture the physical structure of the system. Behaviour Physical Components containing the Physical Functions transitioned from the Logical Architecture layer are allocated to Node Physical Components. Physical links between these Node Physical Components are then defined, forming up the Physical Architecture. Finally, subsystem requirements are allocated to the related physical components when applicable.
- **Cross-Layer (Common)**: additional information of the system is captured in the model as part of the Common Layer. In here, modes and states are captured, as well as the CONOPS for the mission.

7.2 CREAM-IOD Implementation Conclusions

The methodology has been successfully applied during the activity. The model has served as single source of truth during the development, acting as reference point for all teams and containing at all times the most updated information on the project.

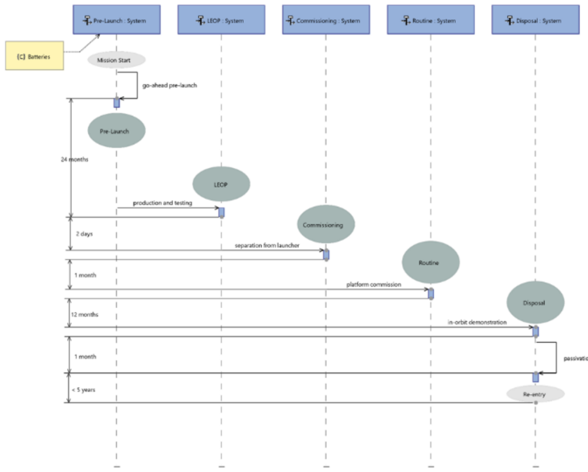

Figure 14. CREAM-IOD CONOPS diagram in Capella

One of the main advantages has been the automated generation of several documentation items, directly from the model; the other one, the possibility to track in real-time the requirements compliance status and verification trace as the design matured.

On the other hand, it has been detected that the methodology adoption by the industry was enhanced by access to proper manuals and identifying from the beginning of the activity a clear workflow between the system engineering function and the rest of teams: this eased the interface between working groups and improved coordination.

8 REFERENCES

[1] ESA Space Debris Mitigation Working Group (2023). *ESA Space Debris Mitigation Requirements.* ESA ESSB-ST-U-007.

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